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A COMPARATIVE ANALYSIS OF TOTAL LIGHTNING OBSERVATIONS AND CLOUD-TO-GROUND LIGHTNING OBSERVATIONS IN THE SOUTHEASTERN UNITED STATES REGION

A Thesis

by

KEITH MICHAEL HUGO

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Approved as to style and content by:

John F. Griffiths
(Chair of Committee)

Richard E. Orville
(Member)

Thomas E. Wehrly
(Member)

Gerald R. North
(Head of Department)

August 1998

Major Subject: Meteorology

ABSTRACT

A Comparative Analysis of Total Lightning Observations and Cloud-to-Ground Lightning Observations in the Southeastern United States Region. (August 1998)

Keith Michael Hugo, B.S., University of Nebraska

Chair of Advisory Committee: Prof. John F. Griffiths

A comparison was performed employing lightning data collected by the Optical Transient Detector (OTD) satellite and the National Lightning Detection Network (NLDN). The feasibility of using total lightning flash data, both intracloud (IC) and cloud-to-ground (CG), collected from the OTD satellite in conjunction with CG lightning flashes detected by the NLDN was demonstrated.

The IC and CG lightning flashes were determined for the period from 1 August 1995 to 31 July 1996. The percentage positive, mean negative multiplicity, positive mean peak current, and negative mean peak current of the CG lightning was determined and compared to the IC lightning.

A positive correlation was found between the percentage of IC lightning and the percentage of positive CG lightning. As the percentage of IC lightning increased from the summer to the winter, the percentage of

positive CG lightning did as well. As the percentage of IC lightning decreased from the winter to the summer, the percentage of positive CG lightning followed.

A negative correlation was found between the percentage of IC lightning and the mean negative multiplicity. The behavior of the mean negative multiplicity was generally opposite of that of the percentage of IC lightning during the year.

DEDICATION

This thesis is dedicated to my wife, Linda who encouraged me and gave me her love and support.

ACKNOWLEDGMENTS

There have been many people who have helped in the completion of my research and this thesis.

Foremost, I wish to express my thanks and gratitude to Prof. John F. Griffiths. With his advice I was guided through the research process and the writing of this thesis.

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TABLE OF CONTENTS

		Page
ABSTRACT		iii
DEDICATION		v
ACKNOWLEDGMENTS		vi
TABLE OF CONTENTS		vii
LIST OF FIGURES		ix
LIST OF TABLES		xi
CHAPTER		
I	INTRODUCTION	1
	1. General	1
	2. Background	3
	3. Region of Study	9
	4. Goal and Objectives	9
II	DATA COLLECTION AND PROCEDURES	12
	1. Data Collection	12
	2. Procedures	13
III	DATA ANALYSIS	22
	1. Aggregate Lightning Flash Data	22
	2. Monthly Lightning Flash Data	35
	3. IC and CG Lightning Flash Characteristics Comparison	55
IV	DISCUSSION	60
	1. Lightning Flash Data	60
	2. CG Lightning Flash Characteristics	63

CHAPTER Page

3. IC and CG Lightning Flash Characteristics Comparison 64

V CONCLUSIONS AND RECOMMENDATIONS 69

1. Conclusions 69
2. Recommendations 72

REFERENCES 74

APPENDIX A 77

VITA 88

LIST OF FIGURES

FIGURE		Page
1	Region of Interest	10
2	Flash Collocation	18
3	OTD and NLDN Lightning Flashes of April 20, 1996, Orbit 13 Prior to Performing Collocation Procedure	19
4	OTD and NLDN Lightning Flashes of April 20, 1996, Orbit 13 After Performing Collocation Procedure	21
5	OTD Versus NLDN Lightning Flashes	24
6	OTD and NLDN Lightning Flashes of December 20, 1995, Orbit 2	26
7	OTD and NLDN Lightning Flashes of July 23, 1996, Orbit 2	27
8	03Z Tuesday 23 July, 1995 Surface Analysis Chart	28
9	0235Z Tuesday 23 July, 1995 Radar Summary Chart	29
10	OTD Versus NLDN Lightning Flashes With Outliers Removed	30
11	OTD Versus OTD-NLDN Lightning Flashes	32
12	NLDN Versus OTD-NLDN Lightning Flashes	33
13	OTD Lightning Flashes Versus OTD-NLDN Flash Percentage	34
14	Comparison of Monthly OTD, NLDN, and OTD-NLDN Lightning Flash Totals	42
15	Monthly OTD Versus NLDN Lightning Flashes	43
16	Monthly OTD Versus OTD-NLDN Lightning Flashes	44

FIGURE Page

17 Monthly OTD Versus IC/CG Lightning Flashes 46

18 Monthly NLDN Versus OTD-NLDN Lightning Flashes 47

19 CG Lightning Flashes as a Percentage of Total Lightning Flashes Observed by the OTD Satellite and Flash Groups per Month 48

20 Monthly Percentage and Range of CG Lightning Flashes as a Percentage of Total Lightning Flashes Observed by the OTD Satellite of Flash Groups of at Least 30 Flashes 50

21 Monthly Percentage of Positive CG Lightning Flashes 52

22 Monthly Mean Negative Multiplicity of CG Lightning Flashes ... 53

23 Monthly Positive Mean Peak Current of CG Lightning Flashes .. 54

24 Monthly Negative Mean Peak Current of CG Lightning Flashes 56

25 Monthly Percentage of OTD-NLDN Lightning Flashes Versus Percentage of Positive CG Lightning Flashes 58

26 Monthly Percentage of OTD-NLDN Lightning Flashes Versus Mean Negative Multiplicity of CG Lightning Flashes 59

27 Monthly Percentage of CG Flashes and Total OTD Lightning Flashes 62

28 OTD Flashes and IC/CG Lightning Flashes 65

29 Monthly Percent Positive CG Flashes and Percent OTD-NLDN Lightning Flashes 66

30 Monthly Mean Negative Multiplicity of CG Flashes and Percent OTD-NLDN Lightning Flashes 68

LIST OF TABLES

TABLE Page

1 Coefficient of Determination of Various Lightning Parameters .. 36

2 Raw OTD and NLDN Lightning Flash Data for August............... 37

3 Raw Lightning Flash Data for Period August 1995 to July 1996. 39

4 Adjusted Lightning Flash Data for Period August 1995 to July 1996 40

CHAPTER I

INTRODUCTION

1. General

Lightning has been observed or detected through various means by researchers during their study of lightning characteristics. Many of these studies have been based on electromagnetic principles. The result was biased observations due to the location and range of the sensor. The most successful lightning detection has been restricted to landmasses thereby excluding the majority of the Earth's surface. The local lightning detector has evolved into a nationwide network, which has greatly enhanced the study of lightning. The contiguous United States is covered by a network of lightning detectors enabling researchers, and other interested parties from the government and private sector, to benefit from the detection and mapping of cloud-to-ground lightning flashes.

Recent advances in detection of total lightning from satellites has enabled interesting comparisons of the coincident data. Observations of lightning from satellites have improved in quality and utility. Data collected

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The style of this thesis is that of the *Journal of Geophysical Research*.

from Orbiting Solar Observatory satellites OSO-2 and OSO-5 were analyzed to present a distribution of lightning between 30°N and 30°S latitude [Sparrow and Ney, 1971]. Defense Meteorological Satellite Program (DMSP) satellites subsequently carried optical lightning detectors. However, these satellites lacked the ability to detect lightning except under low light conditions and their spatial resolution was poor [Turman, 1978]. The optical transient detector (OTD), a prototype for the Lightning Imaging Sensor launched aboard the Tropical Rainfall Measuring Mission (TRMM) [Goodman et al., 1996], has enabled the detection of total lightning from space and allowed interesting comparisons of data coincident with ground based detection systems.

This study presents a comparison of the lightning data collected from the ground based National Lightning Detection Network (NLDN) and the space based OTD.

By taking the difference between the cloud-to-ground (CG) lightning detected by the NLDN and the OTD detected lightning it is possible to achieve an estimate of the amount of intracloud (IC) lightning. The IC lightning data can then be compared to the CG lightning.

The percent positive and mean negative multiplicity of the flashes detected by the NLDN can be computed for each corresponding satellite

overpass. These can then be compared to the CG/IC lightning ratio to determine if a relationship exists for the data.

2. Background

2.1. Ground based lightning detection

Lightning observation and detection methods have evolved through various forms. Lightning rates have even been inferred from records of thunderstorm days. Researchers have used lightning flash rate counters and electromagnetic field monitors to measure local lightning flash rate [Turman and Edgar, 1982]. More than 60 years ago cross-loop direction finders were used to track the electrical activity of tropical cyclones [Lyons and Keen, 1994]. Hughes [1967] studied extremely low frequency (ELF) signals from lightning discharges in storms over the Pacific. A very low frequency (VLF) detection system that monitored storms over most of the earth was reported on by Volland et al. [1983]. Two crossed baseline interferometers [Johnson, 1980] were used to collect data on the electrical activity of Hurricane Alicia (1983) [Lyons and Keen, 1994]. Sferics activity was studied by W.B. Freeman, however, it was shown to be biased toward continental areas [Turman and Edgar, 1982]. The Kennedy Space Center, Florida has used the Lightning Detection and Ranging (LDAR) system to monitor very high frequency (VHF) signals from lightning activity as well as a field mill network [Goodman et al., 1996]

The direction finders used to detect cloud-to-ground lightning in the contiguous United States were invented by E. Philip Krider, Carl Noggle, and Martin Uman and were manufactured by Lightning Location and Protection Company, [Orville, 1994] now Global Atmospherics, Inc. [López et al., 1997]. The direction finders (DFs) consist of two orthogonal magnetic-loop antennas, a flat plate electric field antenna and the electronics to process the signals [Orville et al., 1983]. The bandwidth of the antennas is from 1 kHz-350 kHz [Orville, 1991a]. The magnetic field produced by lightning creates a current in the loops and by geometry the angle to the lightning flash can be determined. The 180° ambiguity is removed with the flash polarity determined by an electric field antenna. The DFs use the differences in waveform to enable the sensor to respond only to CG flashes [Orville et al., 1983]. Flash location is determined by triangulation. At least two DFs are required to locate a flash. If three or more DFs are used, a more precise location is obtained [López et al., 1997]. The DFs have a nominal range of 400 km and flash polarity is reliably recorded within 600 km [Brook et al., 1989].

Time-of-arrival (TOA) lightning detection systems use the principle of arrival time differences of the electromagnetic pulse of lightning discharges. The Lightning Position and Tracking System (LPATS) was developed and operated by Atlantic Scientific Corporation which later became Atmospheric

Research Systems Inc. (ARSI) [Watson et al., 1995]. Arrival times of the peak amplitude of the electromagnetic pulse between pairs of stations defined hyperbolas. With four sensors detecting the pulse, a location could be determined [Watson et al., 1995].

The development of DFs [Krider et al., 1976] and TOA techniques for lightning detection enabled the establishment of lightning detection networks. In 1976, the Bureau of Land Management (BLM) commissioned a regional lightning detection network in the western states [Orville, 1991a]. The National Severe Storms Laboratory (NSSL) built a network in 1979 in Oklahoma [Orville, 1991b]. Also in 1979, Tampa Electric Co. installed a lightning detection network funded by the U.S. Department of Energy [Shepard, 1986]. By 1983, the State University of New York at Albany (SUNYA) had installed a network of 10 DFs along the East Coast [Orville et al., 1983]. Realizing the potential value of a larger network, the Electrical Power Research Institute (EPRI) funded a program to expand the SUNYA network to 26 DFs covering the East Coast from southern Maine to eastern Alabama [Shepard, 1986]. The three regional networks, BLM's, NSSL's, and SUNYA's grew and were combined into the National Lightning Detection Network in 1989 [Orville, 1991b]. The National Weather Service (NWS) contracted with Atmospheric Research Systems Inc. (ARSI) in 1992, to provide a national lightning detection system. ARSI used TOA techniques to

detect lightning [Watson et al., 1995]. Since 1992, operation of the NLDN of DFs was performed by GeoMet Data Services (GDS) [Samsury and Orville, 1994; López et al., 1997]. In 1993, two lightning detection networks were operating in the contiguous United States [Watson et al., 1995]. In late 1993, ARSI merged with GDS. Now users of the NLDN data receive information based on both techniques [Watson et al., 1995]. GDS and LLP have since became Global Atmospherics, Inc., located in Tucson, Arizona [López et al., 1997; Orville and Silver, 1997]. The NLDN presently consists of over 100 wideband DFs with additional TOA sensors [Orville, 1991b, 1994; Orville and Silver, 1997].

2.2. Observations of lightning from space

Turman [1976] reported on the feasibility of monitoring lightning from space-based sensors. Observations were examined from a USAF Defense Meteorological Satellite Program (DMSP) satellite. The satellite was flown in a sun-synchronous orbit. The earth was observed at local noon and night from this orbit. Because of the background light intensity, lightning detection was only possible at night and only during periods of a new moon. This experiment demonstrated that lightning could be detected optically from space.

Orville and Spencer [1979] used lightning streaks on DMSP visible cloud imagery to observe lightning at dusk and midnight. Turman and Edgar [1982] reported on the Piggyback Experiment sensor on a DMSP satellite. It had the shortcoming of only detecting 2% of the lightning in the field of view. Since the radius of the field of view was so large, it had a location error of 680 km, and could only make lightning observations at dawn and dusk.

Goodman et al. [1988] tested optical sensors aboard a U2 high-altitude aircraft as a design study for a lightning mapping sensor (LMS) on a GOES weather satellite proposed by NASA. The optical pulse sensor (OPS) used observed the 777.4 nm emission line of neutral atomic oxygen. A narrow band interference filter to pass the 777.4 nm emission line and a high-pass filter was placed in front of the OPS. The high-pass filter allowed the light pulses from the lightning flashes to pass but prevented the slow varying signals such as sunlight reflecting from cloud tops to pass. The results of the experiment demonstrated the capability to detect lightning flashes with a spatial resolution of 7-10 km and a temporal resolution of 1 ms. However, it was determined that it would be difficult to distinguish between IC and CG lightning with optical sensors aboard a satellite [Christian et al., 1989].

In April 1995 the Optical Transient Detector (OTD) was launched aboard a satellite [Hecht, 1995]. The OTD was a prototype for the Lightning Imaging Sensor launched in November 1997 on the Tropical Rainfall Measuring Mission (TRMM) [Goodman et al., 1996]. The satellite is in a precessing orbit of 740 km with a inclination angle of 70°. This orbit allows the OTD satellite to observe areas of the Earth at differing times of the day. The OTD satellite revisits a particular point on Earth at the same local hour approximately every 55 days. The instantaneous field of view is more than 1300 km x 1300 km. The OTD was designed to have a 10 km spatial resolution within its field of view, a temporal resolution of 2 ms, and a 90% probability of detection day or night [Buechler et al., 1996].

Both IC and CG lightning flashes are observed by the OTD. An event is the occurrence of a single pixel exceeding the threshold. Multiple optical pulses could be counted as one event if they occur within the 2 ms temporal resolution of the sensor. An OTD flash may be one or more events separated by 330 ms or less.

Boccippio et al. (1997) reported that the likely spatial resolution of the operational satellite is about 8 km at nadir, 11 km on average and is between 18-23 km at the corners of the field of view. It was also presented that location errors may be introduced due to navigational errors in the Microlab-1 satellite. The combination of these two errors lead to possible

position errors of typically 20-40 km, with 25% of the position errors greater than 100 km.

In order to reduce the false detection rate, software filters were used at various thresholds. For the period 20 July 1995 - 23 October 1996, the threshold used resulted in a estimated OTD CG detection efficiency of 56% ±10%.

3. Region of Study

The region of interest for this study is the Southeastern United States and adjoining coastal waters. For the purpose of this study, this is defined with latitude bounds of 25°00′N and 36°30′N and longitude bounds of 75°00′W and 98°00′W as depicted in Figure 1. These boundaries include the coast of North Carolina extending south to include the Florida peninsula, west to include the cities Corpus Christi and Austin, north to include Dallas Texas, Oklahoma City and Tulsa, Oklahoma, and east approximately along the North Carolina-Virginia border, an area of approximately 2,800,000 km^2. The period of this study is one year, 1 August 1995 - 31 July 1996.

4. Goal and Objectives

The goal of this research is to demonstrate the feasibility of using total lightning flash data (IC and CG) collected from the OTD satellite in

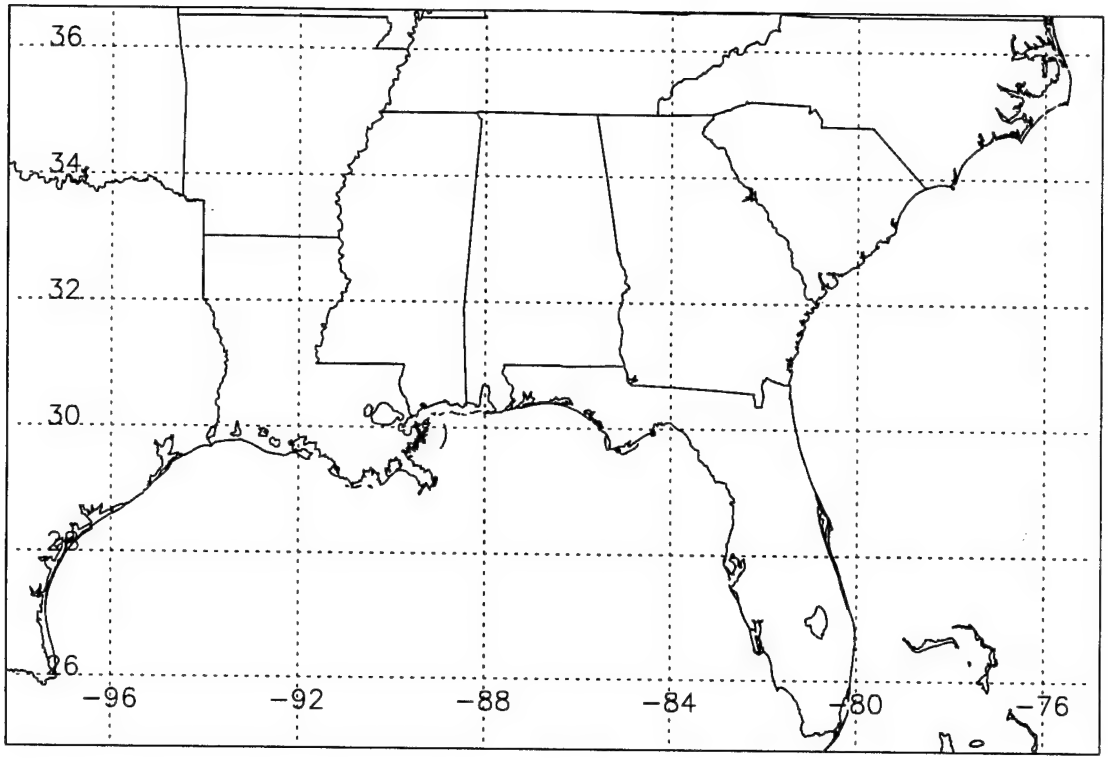


Figure 1. Region of Interest

conjunction with CG lightning flashes recorded by the NLDN so as to derive separately the IC and CG lightning activity in the region of interest. These data will be used to examine a possible seasonal relationship of the IC lightning to CG lightning flash data and of percent positive and negative multiplicity of the lightning data detected by the NLDN.

To accomplish this goal the following objectives will be met:

1. Collect lightning flash data detected by the OTD satellite and the NLDN in the region of interest and determine lightning flashes detected by the NLDN occurring synchronously with the flashes detected by the OTD satellite.

2. The IC lightning (derived from the difference of the total lightning detected by the OTD satellite and the CG lightning detected by the NLDN), will be compared to CG lightning detected by the ground based NLDN.

3. The percentage of positive lightning flashes detected by the NLDN will be determined and compared to the IC lightning to examine the monthly and seasonal variations between these two parameters.

4. The mean negative multiplicity of the lightning flashes detected by the NLDN will be determined and compared to the IC lightning to examine the monthly and seasonal variations between these two parameters.

CHAPTER II

DATA COLLECTION AND PROCEDURES

1. Data Collection

1.1. OTD lightning flash data

The OTD lightning flash data were obtained from 8 mm data tapes of the archived data from the NASA Marshall Space Flight Center in Huntsville, Alabama stored in the Meteorology Department at Texas A&M University. The OTD data consist of orbit files for each orbit of the satellite. The data were written to the tapes in hierarchical data format (HDF). There are approximately 15 orbit files for each day. The OTD data used for this study for each lightning flash consist of: day, month, year, hour, minute, seconds for time of each occurrence, and latitude and longitude for position and a HDF scientific data set (SDS) file containing the viewtimes for each orbit of the satellite. Viewtimes are measured in seconds and represent times of reliable information from the OTD satellite.

1.2. NLDN lightning flash data

The NLDN data were obtained from flash files archived on microcomputers in the Meteorology Department at Texas A&M University. The NLDN data consist of files for each month. The NLDN lightning flash

data are stored as binary files. The data from the NLDN used for this study for each lightning flash consist of: day, month, year, hour, minute, seconds for time of each occurrence, latitude and longitude for position, multiplicity, polarity, and peak current of the first-stroke.

2. Procedures

2.1. OTD data handling procedures

After the data were extracted from the tape, each orbit file was processed using a computer program written in C. The C program read the HDF orbit file and determined if the file contained data in the area defined with latitude bounds of 20°00´N and 50°00´N and longitude bounds of 63°00´W and 125°00´W (area 1). All the data contained inside these bounds were written to a smaller HDF file, a HDF SDS file containing the viewtimes for the bounded area, and a file written in ASCII format containing day, month, year, hour, minute, seconds, latitude and longitude for each lightning flash.

It was then determined that the study area would be restricted to the area defined with latitude bounds of 25°00´N and 36°30´N and longitude bounds of 75°00´W and 98°00´W (area 2). An Interactive Data Language (IDL) program was used to restrict the data to the new boundaries and

write the data in ASCII format to a file containing only flashes in the study area.

The remaining data were compared to viewtimes of the OTD satellite. Since only flashes under the positive viewtime areas of the satellite are considered reliable, an IDL program was used to include only flashes with positive viewtimes using information from the corresponding HDF SDS file of viewtimes.

It was discovered that the lightning flash data were not in chronological order. An IDL program was used to reorder the data.

A UNIX shell script was used with each group of flash files to determine the times of the first and last lightning flash for each orbit file and write these times to a file. This script was first run on the group of flashes in area 1. The second time the script was run on the group of flashes in area 2. It was used a third time on the group of flashes with positive viewtimes and a fourth time on the reordered data.

2.2. NLDN data handling procedures

An IDL program was run on a microcomputer containing the archived NLDN flash data. The program was run using the first run of the first and last OTD lightning flash times. Since the times recorded for the OTD flashes were recorded in milliseconds and the NLDN flashes available for this study

were recorded in whole seconds, the first flash times of the OTD data were rounded down to the nearest whole second and the last flash times were rounded up to the nearest whole second. The program read the binary NLDN flash files stored on the microcomputer. The program determined the occurrence of NLDN flashes from the first and to the last OTD flash within the bounds of area 1, for each satellite orbit over the area. The flashes were written to a files in binary format and in ASCII format corresponding to each satellite orbit over the area. Both the binary and ASCII files from the microcomputer were sent via file transfer protocol (ftp) to a disk mounted on the UNIX computer system network in the Meteorology Department at Texas A&M University where the remaining data processing was performed.

As stated earlier, the study area would be restricted to area 2. An Interactive Data Language (IDL) program employing the first and last flash times of the second run of the shell script was used to restrict the data to the new boundaries and write the data to files in binary format and in ASCII format of only flashes in the study area.

The remaining data were then compared to the same viewtime files as the OTD data to ensure that only NLDN flashes occurring under the OTD swath were included in the data set. Since only OTD flashes under the positive viewtime areas of the satellite are considered reliable, an IDL

program was used to include only the NLDN flashes with positive viewtimes using information from the corresponding HDF SDS file of viewtimes. The program also used the first and last flash times of the third run of the shell script to restrict the NLDN flashes to the times of the OTD flashes.

When it was discovered that the OTD flashes were not in chronological order, the shell script was run a fourth time on the original set of OTD flashes in area 1 to get a new set of first and flash times. This necessitated re-accomplishing the entire set of previously accomplished procedures.

2.3. Collocating the OTD and NLDN flashes

Since the viewtimes are not equal across the satellite swath, a group of OTD flashes could not be compared to a group of NLDN flashes without out time-weighted averaging the NLDN flashes. However, this procedure did not take into account that NLDN flashes could be included in the data set if they occurred from the time of the first OTD flash through the time of the last flash while not occurring under the foot print of the satellite as it moves latitudinally across the study area. An alternate procedure was employed adapting an approach used by Boccippio et al., (1997), to include NLDN flashes if they occurred within ±1° of latitude and longitude and ±1 sec of each OTD flash.

The problem with this procedure is illustrated in Figure 2. In a case where more than one NLDN flash met the time and location criteria for collocating a flash, those flashes would be included in the data set of NLDN flashes. The example in Figure 2 shows 2 OTD flashes. The box around each represents the time and space restrictions for collocating a NLDN flash. In this example, 2 NLDN flashes were erroneously matched with each OTD lightning flash. The collocation method however, did not allow NLDN flashes to be counted twice. In this example the total OTD lightning flashes would have been 2 and the total NLDN lightning flashes 3. Out of the 355 satellite overpasses used in this study only in 1 case did the collocation method result in more NDLN than OTD flashes. In this case, 4 OTD flashes were detected and were matched with 7 OTD flashes. The infrequency with which this problem occurred increased the confidence in the procedure.

Despite the weakness of the collocation algorithm, the procedure yielded favorable results. It also eliminated the need to weight the NLDN flashes, took into account the locational and temporal errors of the two detection systems, and resolved the problem of including NLDN flashes not under the foot print of the OTD satellite. Figure 3 shows, as an example, the OTD lightning flashes, the contoured viewtimes of the satellite, and the NLDN lightning flashes collected on orbit 13, on April 20, 1996 before the

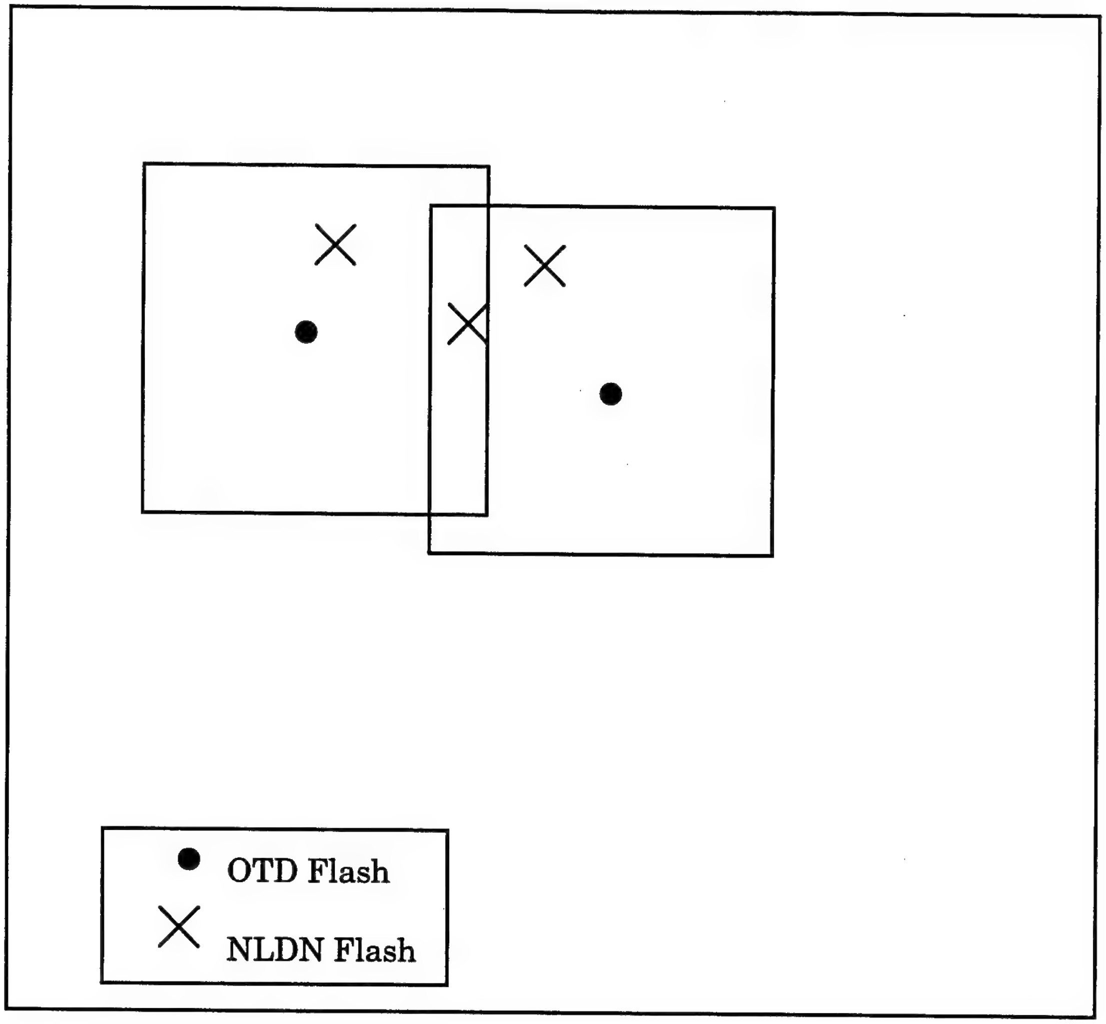


Figure 2. Flash Collocation

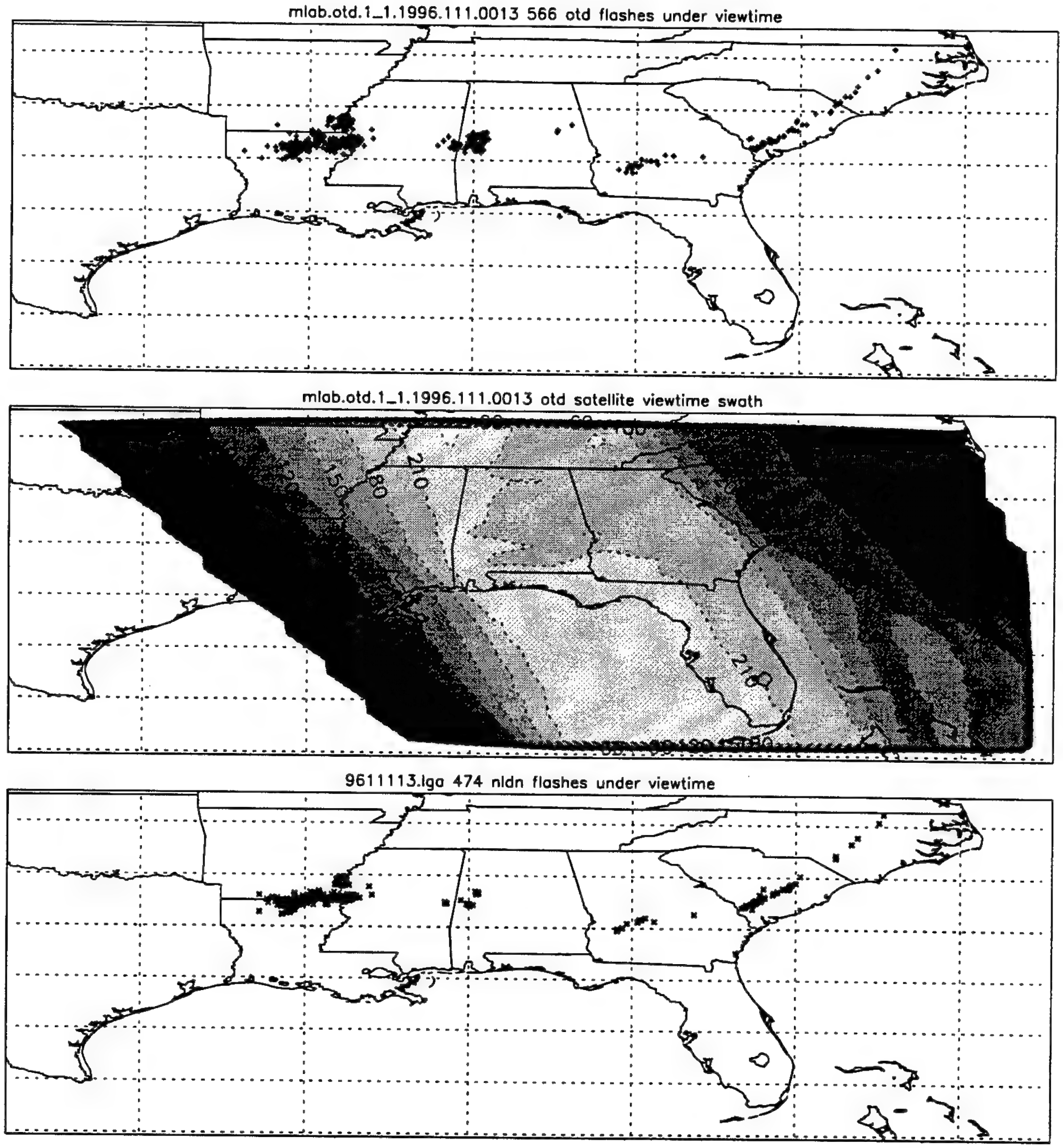


Figure 3. OTD and NLDN Lightning Flashes of April 20, 1996, Orbit 13 Prior to Performing Collocation Procedure

collocation procedure was performed on the data. The top panel of Figure 3 shows the 566 OTD lightning flashes that were detected by the OTD satellite. The middle panel shows the satellite swath with contoured viewtimes (in seconds) as the satellite passed over the region of interest from north to south. The bottom panel shows the 474 lightning flashes that were detected by the NLDN from the time of the first detected OTD lightning flash until the time of the last OTD lightning flash. Figure 4 shows in the bottom panel the 225 NLDN lightning flashes that were collocated with the 566 OTD flashes shown in the top panel of the figure. It is apparent that the collocation procedure was effective in eliminating NLDN lightning flashes that did not occur within the parameters of the collocation procedure.

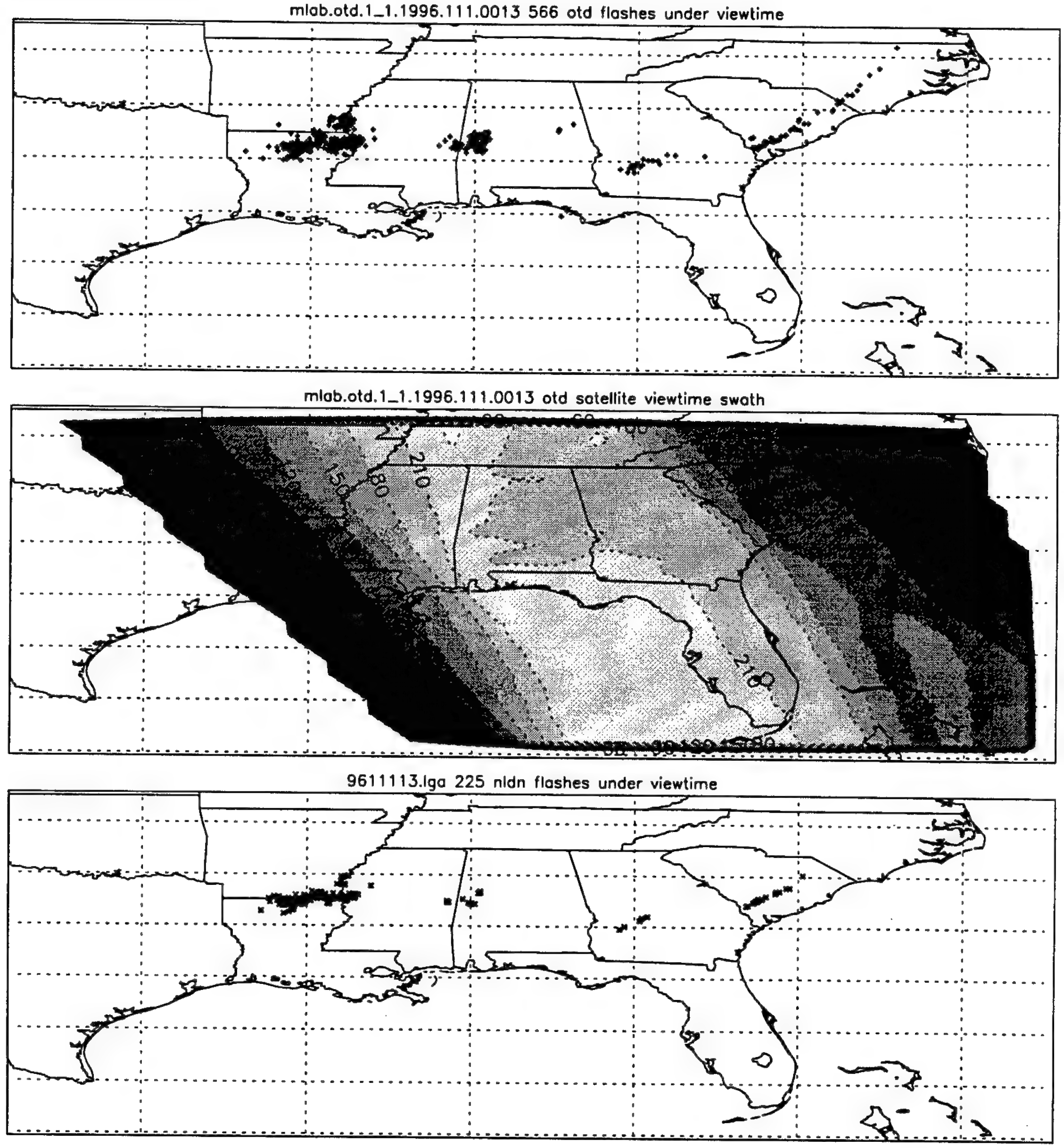


Figure 4. OTD and NLDN Lightning Flashes of April 20, 1996, Orbit 13 After Performing Collocation Procedure

CHAPTER III

DATA ANALYSIS

1. Aggregate Lightning Flash Data

Using the collected data, an estimate of the number of IC lightning flashes were determined by taking the difference between the OTD lightning flashes and the CG lightning flashes detected by the NLDN. The lightning flash data collected from the NLDN were used to determine the characteristics of the CG lightning.

The percent positive of CG flashes were determined from the number of positive flashes divided by the total number of CG flashes (positive and negative) multiplied by 100. The multiplicity of a CG lightning flash is the number of strokes in a flash. The mean negative multiplicity for each group of flashes was determined by dividing the total multiplicity for the negative flashes by the number of negative CG flashes in the group. The first-stroke positive mean peak current was determined for each group of flashes by dividing the total positive peak current by the number of positive flashes. Likewise, the first-stroke negative mean peak current was determined for each group of negative lightning flashes. The percent positive, the mean negative multiplicity, the positive mean peak current, and the negative mean peak current was determined for each group of flashes for each

satellite overpass and for each month of flashes collected from each satellite overpass.

During the year period of this study, 355 satellite passes detected lightning over the study area. During the satellite overflights 29,808 OTD flashes and 9214 NLDN flashes were collected. In order to determine the relationship of the OTD lightning flashes and the NLDN lightning flashes, the corresponding flashes were plotted for each group of flashes collected from each satellite overpass the result is shown in Figure 5. A simple linear regression model was used. This model can be stated as:

$$Y = \beta_0 + \beta_1 X + \varepsilon, \qquad (1)$$

where Y is the dependent variable and β_0 and β_1 are termed the intercept and the slope of the line. The terms β_0 and β_1 are estimated by b_0 and b_1. and Y becomes the predicted value of Y. The values of β_0 and β_1 were determined by the least squares method resulting in the line of best fit. It should be noted that the independent variable is a component of the dependent variable in Figures 5, 8, 9, 11, 13, 14, and 15. For the flash groups plotted in Figure 5 the intercept was -2.04 and the slope of the line of best fit was 0.33. The coefficient of determination (r^2) was determined to be 0.81. Thus approximately 81% of the variability in the NLDN lightning can be related to the OTD lightning flashes.

Two outliers were identified, in the plot (each outlined with a box). The first case occurred on the second orbit of the day on December 20, 1995

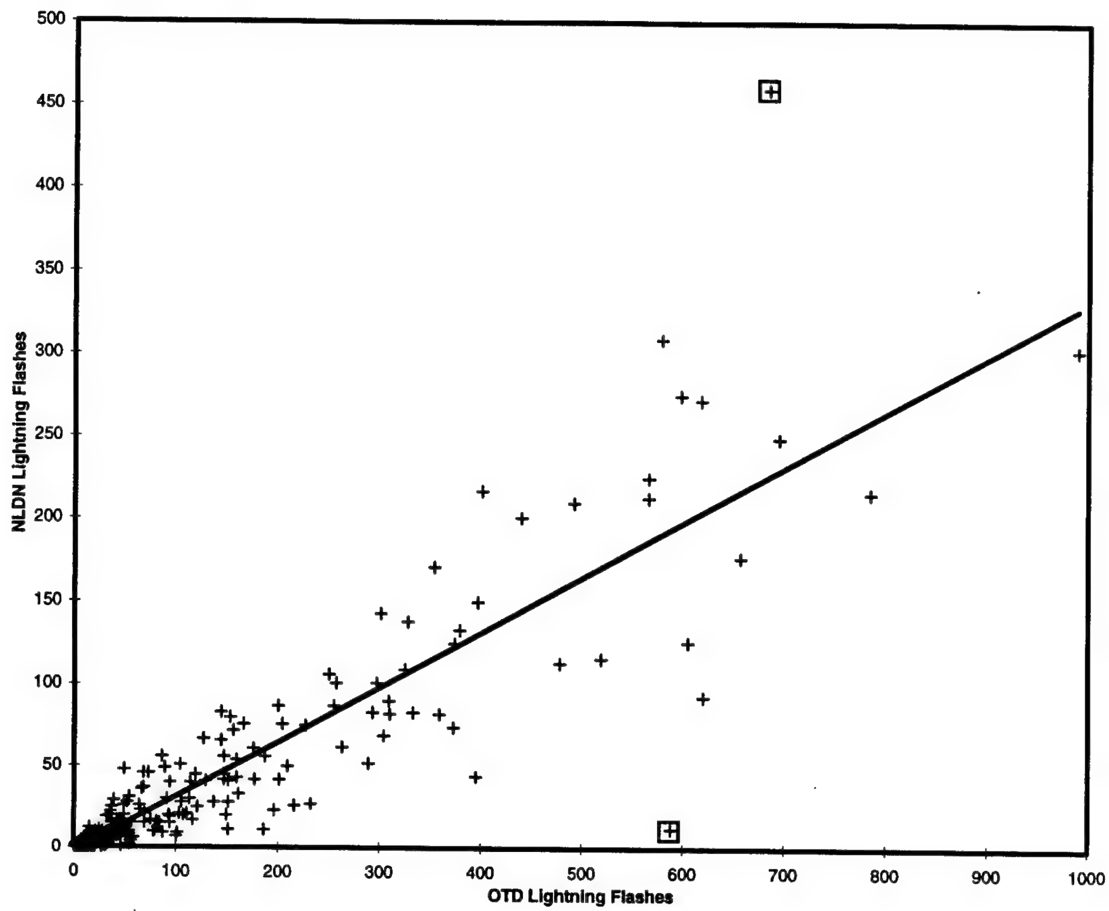


Figure 5. OTD Versus NLDN Lightning Flashes (Outliers outlined with a box)

shown in Figure 6. During this satellite overpass, 588 OTD flashes were collected while only 12 NLDN flashes were collected. The entire group of these flashes occurred off the coast of South Carolina over the water. Two possible causes are the decreased detection efficiency of the NLDN with increased distance from the land or the IC/CG ratio may be greater over the oceans than over the land.

In the second case on the second orbit of the day on July 23, 1996 shown in Figure 7, 684 OTD flashes and 460 NLDN flashes were collected from storms over western Tennessee extending to Oklahoma. Figure 8 shows a portion of the Surface Analysis Chart. The chart shows a cold front extending across Indiana through Kansas. Ahead of this cold front thunderstorms developed and produced the lightning flashes that were detected by the two systems. A portion of the Radar Summary is shown in Figure 9. Echo tops for these storms were as high as 17 km (57,000 ft). The intensity of these storms is a possible explanation for the low IC/CG ratio collected during this satellite overpass. This storm was an extreme example, other storms may have been as intense as this one but that was not investigated.

A regression analysis was conducted on the data with the two outliers removed. Figure 10 shows the plot and the resulting line of best fit. The for the intercept for the line was -1.65 and the slope was 0.33. The r^2 increased to 0.87 when the two outliers were removed. Thus the removal of the two

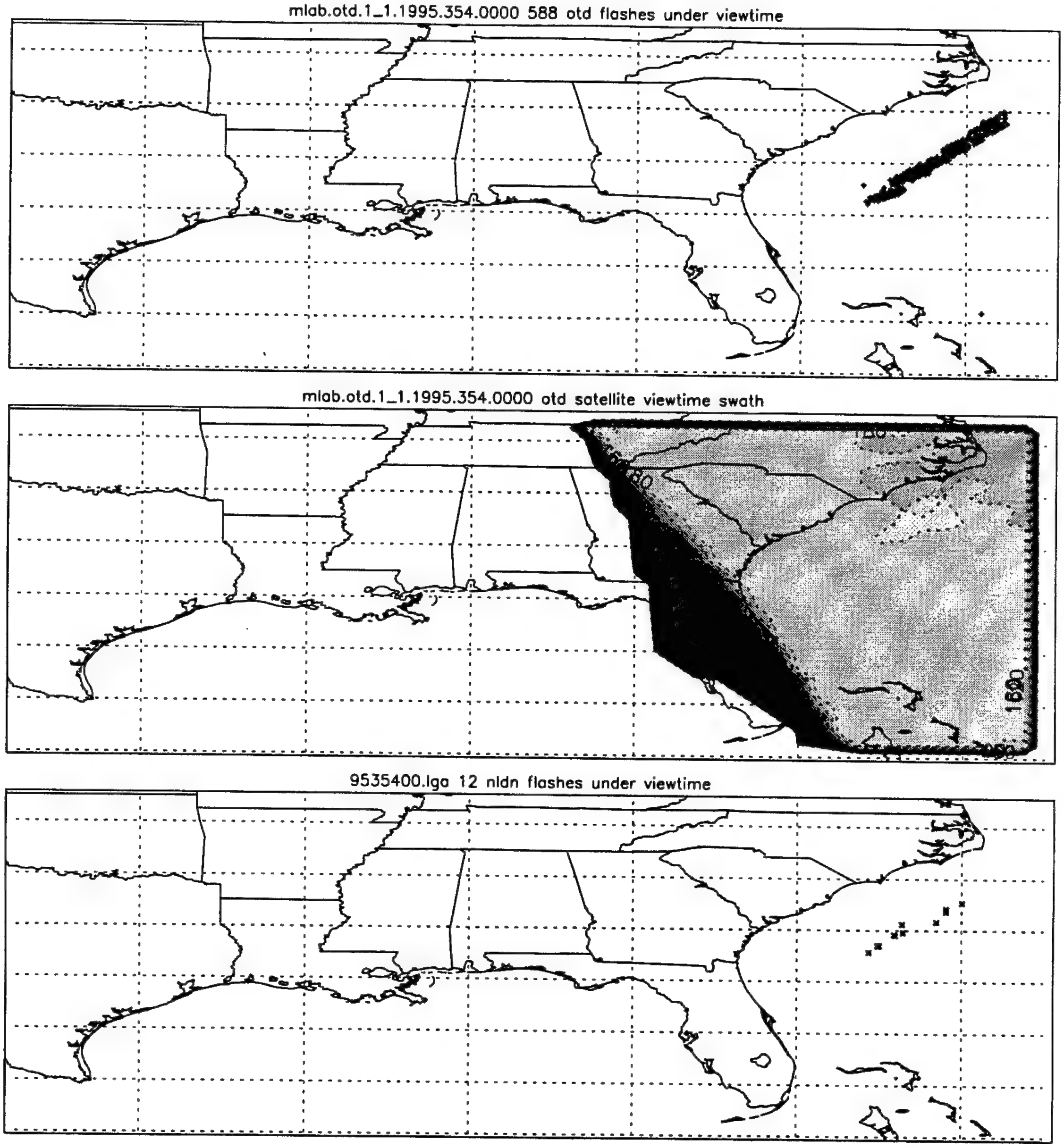


Figure 6. OTD and NLDN Lightning Flashes of December 20, 1995, Orbit 2

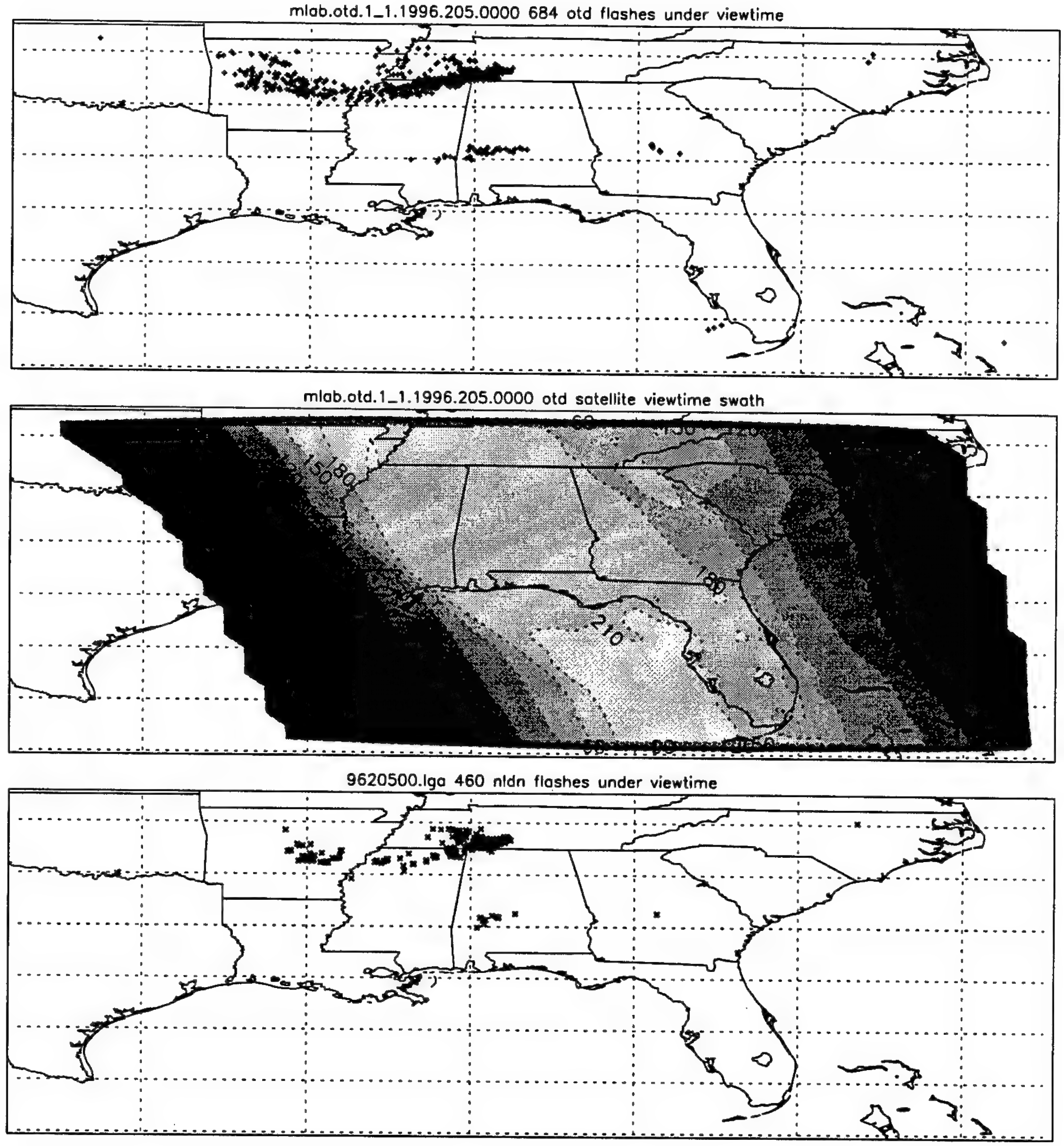


Figure 7. OTD and NLDN Lightning Flashes of July 23, 1996, Orbit 2

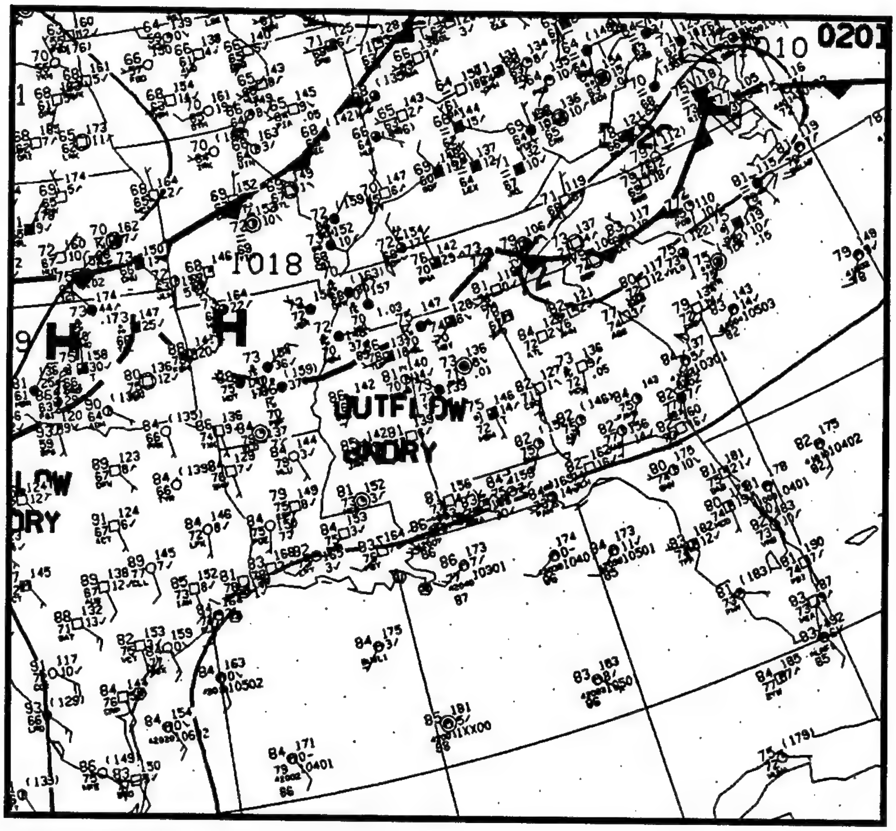


Figure 8. 03Z Tuesday 23 July, 1995 Surface Analysis Chart

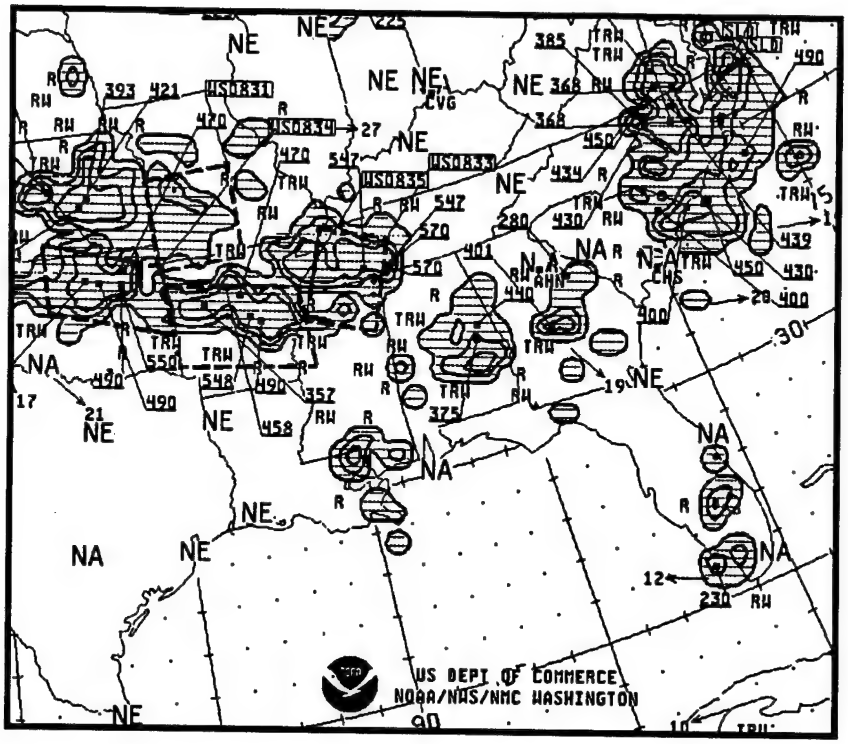


Figure 9. 0235Z Tuesday 23 July, 1995 Radar Summary Chart

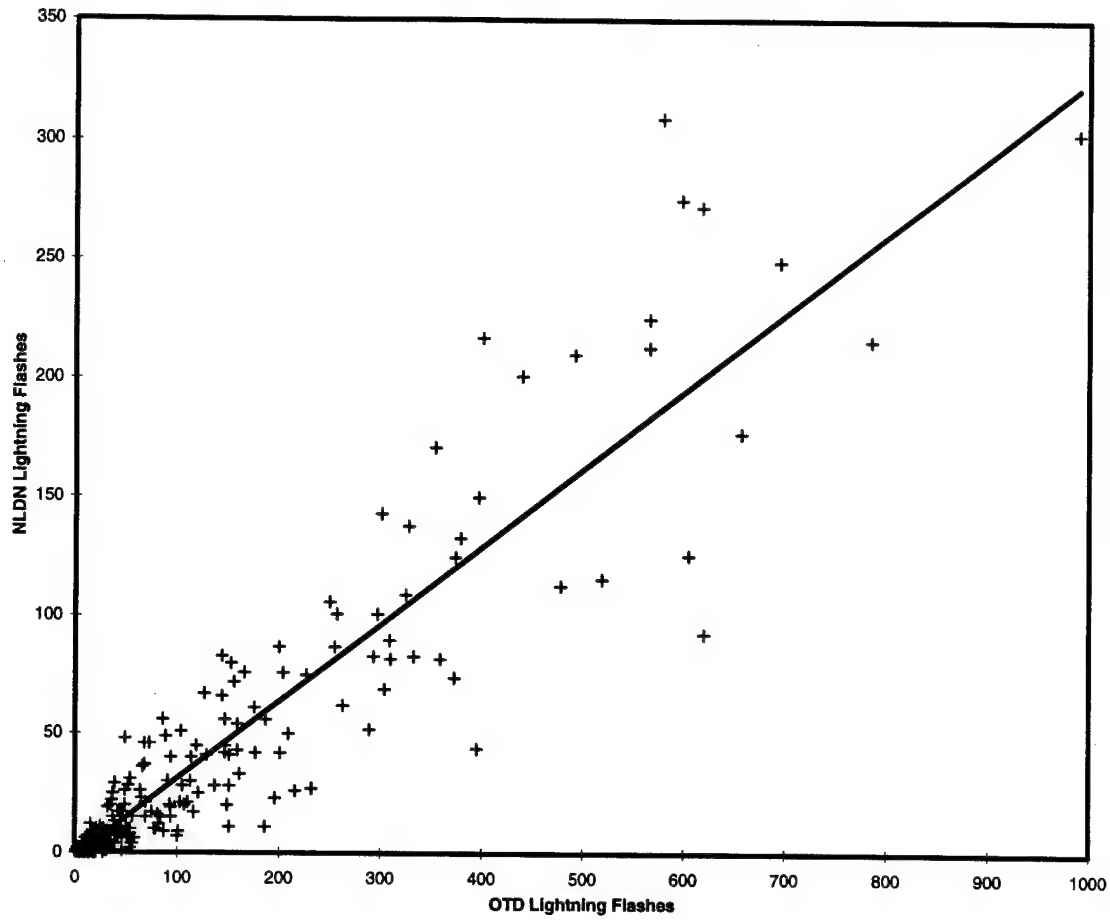


Figure 10. OTD Versus NLDN Lightning Flashes With Outliers Removed

outliers resulted in approximately 87% of the variability in the NLDN lightning being related to the OTD lightning flashes.

From the OTD and NLDN flashes collected during each satellite pass an estimate of the IC flashes were determined. Figure 11 shows the OTD flashes for each satellite pass plotted against the difference of the OTD and NLDN flashes. The line of best fit was determined to have an intercept of 2.04 and slope of 0.67. The r^2 in this case was 0.94, which indicates that approximately 94% of the number of derived IC flashes for each satellite pass can be associated to the OTD lightning flashes.

The plot of NLDN flashes versus the difference of the OTD and NLDN flashes is shown in Figure 12. There was more variation between the values of NLDN and estimated IC flashes than the OTD and estimated IC flashes. This was evidenced by the smaller $r^2 = 0.59$. The slope of the line of best fit was 1.42 and the intercept was 25.06.

The OTD flashes plotted against the difference of the OTD and NLDN flashes as a percentage of the total number of flashes for each satellite pass is shown in Figure 13. The wide variation from 0 to 100% is due to the group of small numbers of flashes collected during each satellite pass. With only 1 OTD flash detected, the presence or absence of 1 NLDN can result in either 0 or 100% estimated IC flashes. The intercept and slope for this plot were 77.98 and -0.03 respectively. The r^2 for the OTD versus the percentage of IC

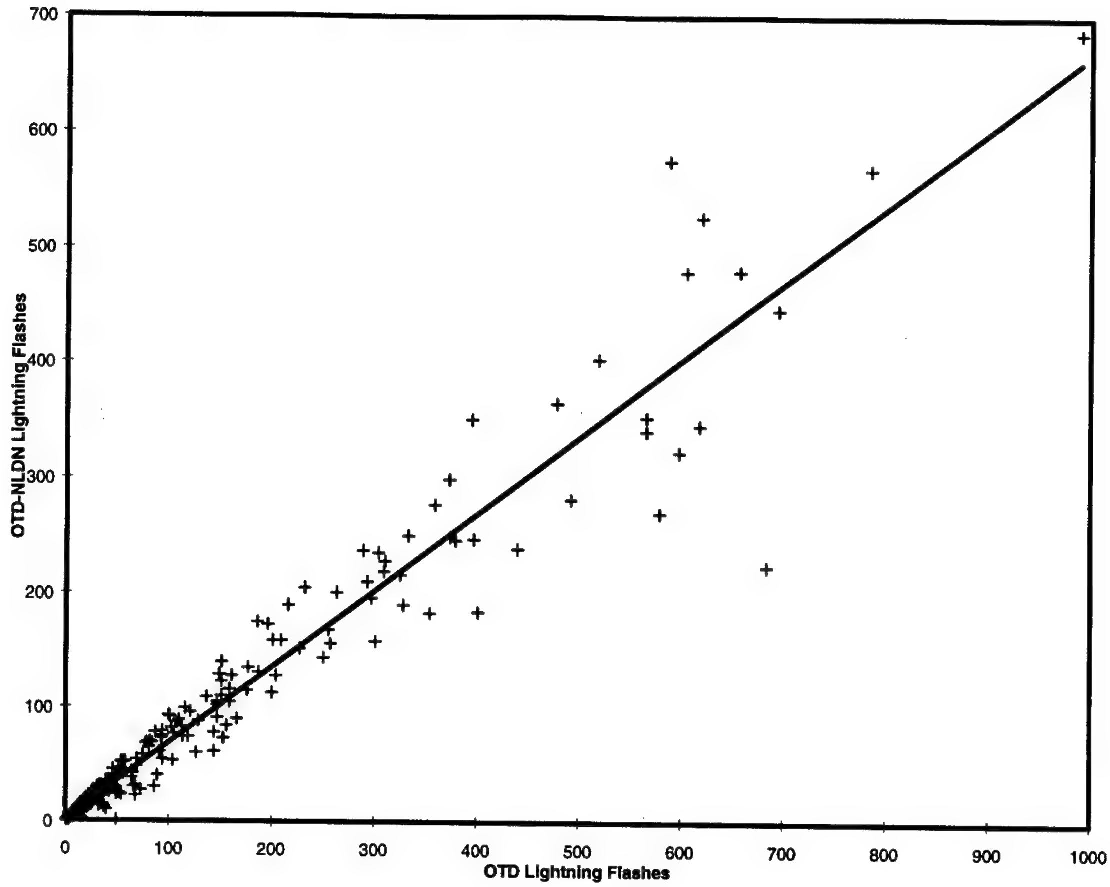


Figure 11. OTD Versus OTD-NLDN Lightning Flashes

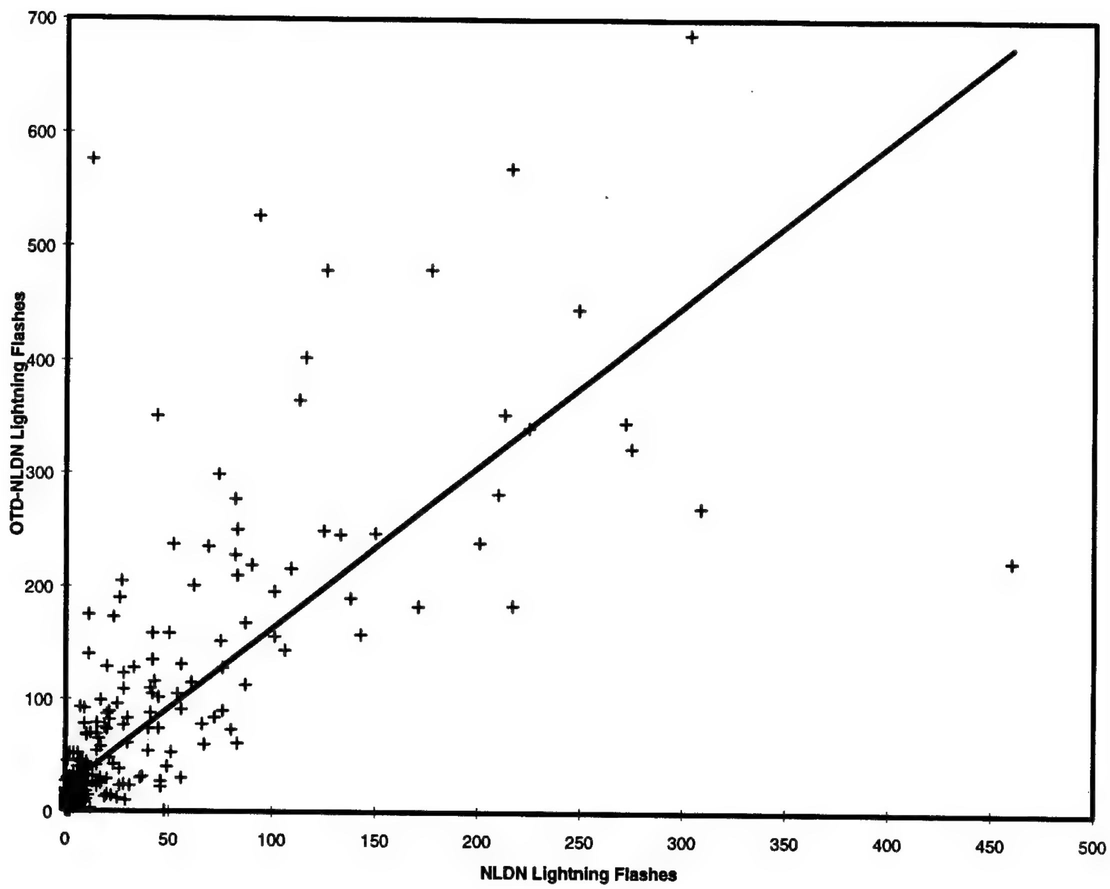


Figure 12. NLDN Versus OTD-NLDN Lightning Flashes

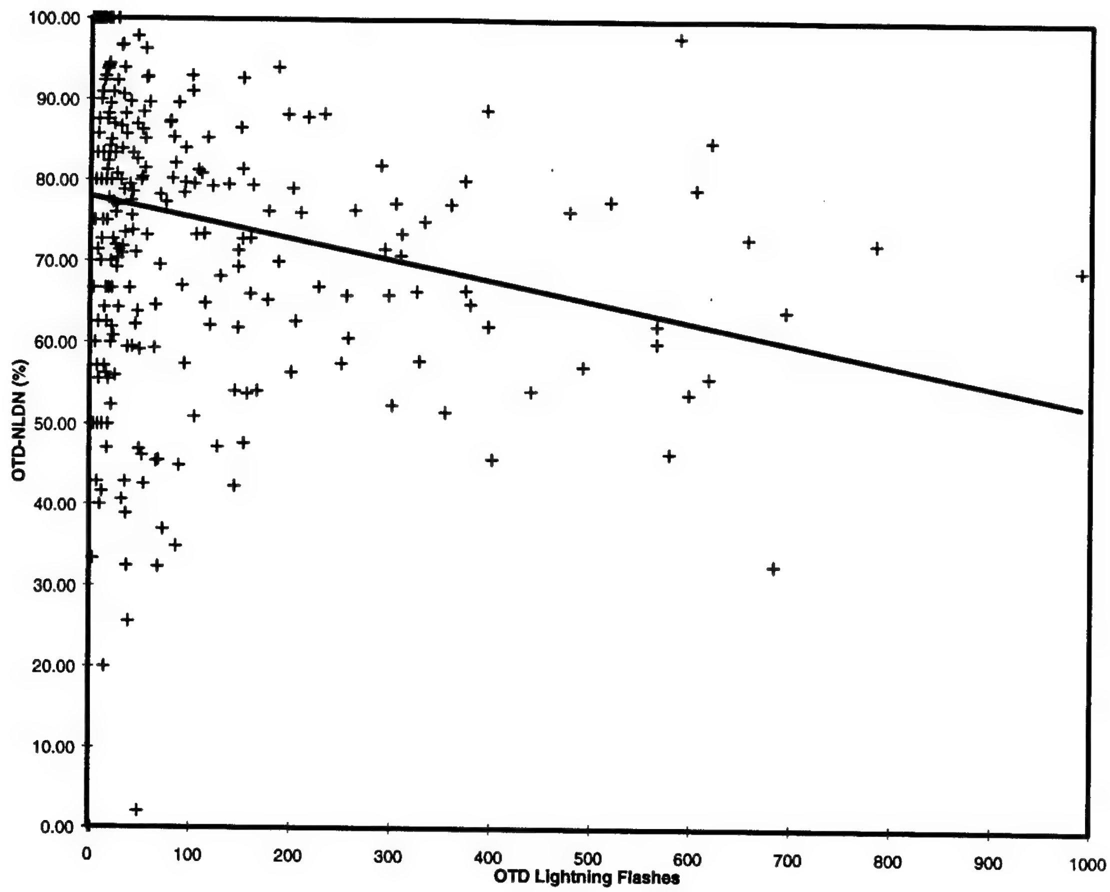


Figure 13. OTD Lightning Flashes Versus OTD-NLDN Flash Percentage

flashes was 0.03. The coefficient of determination for other parameters was determined and are listed in Table 1.

2. Monthly Lightning Flash Data

2.1. OTD, NLDN and IC Comparisons

The lightning flash data were analyzed beginning with the observation for the first month of the study. The raw (unadjusted for the detection efficiencies of the two detection systems) lightning flash data for August 1995 collected from the OTD and NLDN for each satellite overpass when the OTD recorded at least one lightning flash are summarized in Table 2. The satellite orbits are numbered beginning with 99 for the first orbit of the day, 0 for the second orbit and so on. For these 39 satellite overpasses when lightning was detected by the OTD satellite in the region of interest during this month, a group consisting of at least one NLDN flash was also collected in 34 of the cases. The derived percentage of CG flashes for the month was 39.65%. The percentage of positive CG flashes was 8.23%. The negative multiplicity was 2.26, the positive mean peak current was 16.90 kA, and the negative mean peak current for the month was -30.68 kA. The tables for the raw lightning flash data for the remaining 11 months of the study are found in Appendix A.

Table 1. Coefficient of Determination of Various Lightning Parameters

Parameters	coefficient of determination(r^2)
OTD Versus Percent Positive	0.00
OTD Versus Negative Multiplicity	0.03
OTD Versus Positive Mean Peak Current	0.02
OTD Versus Negative Mean Peak Current	0.01
NLDN Versus Percent Positive	0.00
NLDN Versus Negative Multiplicity	0.04
NLDN Versus Positive Mean Peak Current	0.01
NLDN Versus Negative Mean Peak Current	0.02
OTD–NLDN Versus Percent Positive	0.00
OTD–NLDN Versus Negative Multiplicity	0.02
OTD–NLDN Versus Positive Mean Peak Current	0.03
OTD–NLDN Versus Negative Mean Peak Current	0.01
Percentage OTD–NLDN Versus Percent Positive	0.01
Percentage OTD–NLDN Versus Negative Multiplicity	0.02
Percentage OTD–NLDN Versus Positive Mean Peak Current	0.01
Percentage OTD–NLDN Versus Negative Mean Peak Current	0.00

Table 2. Raw OTD and NLDN Lightning Flash Data for August

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
99	213	8/1/95	25	7	18	28.00	14.29	2.2	24.8	-47.8
12	213	8/1/95	3	0	3	0.00	.	.	.	.
13	213	8/1/95	201	42	159	20.90	16.67	2.8	29.0	-27.7
4	216	8/4/95	16	3	13	18.75	0.00	1.7	0.0	-47.5
12	217	8/5/95	492	210	282	42.68	10.48	2.3	16.9	-33.3
4	218	8/6/95	16	7	9	43.75	28.57	1.6	20.2	-35.6
13	218	8/6/95	9	4	5	44.44	0.00	1.8	0.0	-27.1
4	221	8/9/95	3	1	2	33.33	0.00	1.0	0.0	-19.3
12	221	8/9/95	166	76	90	45.78	5.26	2.2	10.4	-32.0
4	222	8/10/95	19	2	17	10.53	0.00	3.5	0.0	-26.1
12	222	8/10/95	65	23	42	35.38	4.35	1.8	11.5	-46.5
13	222	8/10/95	153	80	73	52.29	5.00	2.7	10.5	-27.6
3	223	8/11/95	34	9	25	26.47	0.00	1.1	0.0	-42.6
12	223	8/11/95	75	17	58	22.67	5.88	1.6	6.1	-12.6
3	225	8/13/95	2	0	2	0.00	.	.	.	.
11	226	8/14/95	304	69	235	22.70	8.70	2.7	17.8	-33.4
4	227	8/15/95	3	1	2	33.33	0.00	2.0	0.0	-69.0
12	227	8/15/95	328	138	190	42.07	7.25	2.2	8.6	-27.3
2	228	8/16/95	105	28	77	26.67	0.00	1.6	0.0	-36.9
8	229	8/17/95	1	0	1	0.00	.	.	.	.
9	229	8/17/95	114	40	74	35.09	0.00	2.1	0.0	-30.8
1	230	8/18/95	14	1	13	7.14	0.00	1.0	0.0	-26.5
10	230	8/18/95	618	272	346	44.01	4.41	2.0	13.2	-29.7
1	232	8/20/95	579	309	270	53.37	12.94	2.5	18.3	-25.0
0	233	8/21/95	1	1	0	100.00	0.00	3.0	0.0	-53.0
1	233	8/21/95	104	51	53	49.04	7.84	2.0	27.4	-29.0
0	234	8/22/95	45	17	28	37.78	23.53	2.4	15.5	-28.1
8	234	8/22/95	39	13	26	33.33	7.69	2.0	4.0	-51.9
1	235	8/23/95	20	8	12	40.00	0.00	2.1	0.0	-25.3
2	236	8/24/95	8	4	4	50.00	0.00	3.0	0.0	-34.6
3	238	8/26/95	1	0	1	0.00	.	.	.	.
4	238	8/26/95	37	15	22	40.54	0.00	2.0	0.0	-29.1
0	239	8/27/95	14	5	9	35.71	40.00	1.7	23.0	-49.5
9	239	2/27/95	4	0	4	0.00	.	.	.	.
0	240	8/28/95	3	1	2	33.33	0.00	2.0	0.0	-33.8
9	240	8/28/95	45	13	32	28.89	0.00	1.8	0.0	-57.0
0	241	8/29/95	31	5	26	16.13	20.00	1.5	14.8	-32.6
8	241	8/29/95	8	3	5	37.50	0.00	1.7	0.0	-91.8
0	242	8/30/95	33	7	26	21.21	0.00	2.0	0.0	-111.4
		TOTAL	3738	1482	2256	39.65				
		MEAN	95.85	38.00	57.85		8.23	2.26	16.90	-30.68

Table 3 summarizes the lightning flash data unadjusted for the detection efficiencies of either the OTD or the NLDN for the entire year of the study. Table 4 lists the OTD lightning flashes, the NLDN lightning flashes, the IC (OTD-NLDN) lightning flashes and the percentage of CG lightning adjusted for the detection efficiencies of the 2 systems. A detection efficiency of 85% was assumed for the NLDN and the NLDN lightning flashes were multiplied by a factor of 1.18. The OTD detection efficiency was estimated to be 56% ±10% for the period of this study. The OTD lightning flashes were multiplied by a factor of 1.52 and 2.17 to account for the range of detection efficiency of the OTD satellite.

The number of OTD flashes for each month is presented in the first line of Table 3. Beginning in August, a trend of generally decreasing OTD flash totals can be seen. This follows a similar trend noted in studies of CG lightning flashes detected by the NLDN [Orville, 1991b, Orville and Silver, 1997]. The minimum number of OTD flashes was in January when only 311 lightning flashes were detected. From January the number of OTD flashes increased steadily through April. In May there was a decrease in the number of OTD flashes followed by the peak in the monthly total of OTD flashes in June. The total for July appears to mark the beginning of the decreasing trend of monthly OTD flashes

The second line of Table 3 lists the totals of the corresponding NLDN lightning flashes. The trend of NLDN flashes follows that seen with the

Table 3. Raw Lightning Flash Data for Period August 1995 to July 1996

	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	TOTAl
TOTAL OTD FLASH	3738	2344	1036	1728	1552	311	899	1838	3483	2292	6454	4133	29,808
TOTAL NLDN FLASH	1482	696	203	379	262	28	186	435	1109	706	2071	1657	9214
TOTAL IC FLASH	2256	1648	833	1349	1290	283	713	1403	2374	1586	4383	2476	20,594
% CG FLASH	39.65	29.69	19.59	21.93	16.88	9.00	20.69	23.67	31.84	30.80	32.09	40.09	30.91
% POS NLDN FLASH	8.23	12.64	19.89	24.01	27.86	21.43	19.89	24.83	16.14	17.71	12.07	13.34	
MEAN NEG MULT	2.26	2.65	2.00	2.10	2.31	2.00	1.72	1.89	2.26	2.55	2.48	2.58	
POS MEAN PEAK CURR (kA)	16.9	18.49	44.92	35.42	35.30	34.68	39.40	33.31	22.23	21.76	18.50	16.87	
NEG MEAN PEAK CURR (kA)	-30.7	-31.69	-40.27	-30.53	-40.43	-42.88	-36.58	-34.88	-27.54	-26.64	-30.70	-29.26	

Table 4. Adjusted Lightning Flash Data for Period August 1995 to July 1996

		AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	Total
TOTAL OTD FLASH	66% DE	5682	3563	1575	2627	2359	473	1366	2794	5294	3484	9810	6282	45,309
	46% DE	8111	5086	2248	3750	3368	675	1951	3988	7558	4974	14,005	8969	64,683
TOTAL NLDN FLASH	85% DE	1749	821	240	447	309	33	219	513	1309	833	2444	1955	10,872
TOTAL IC FLASH	66% DE	3933	2742	1335	2180	2050	440	1147	2281	3985	2651	7366	4327	34,437
	46% DE	6362	4265	2008	3303	3059	642	1732	3475	6249	4141	11,561	7014	53,811
% CG FLASH	66% DE	30.78	23.04	15.24	17.02	13.10	6.98	16.03	18.36	24.73	23.91	24.91	31.12	24.00
	46% DE	21.56	16.14	10.68	11.92	9.17	4.89	11.23	12.86	17.32	16.75	17.45	21.79	16.81

DE = detection efficiency

OTD flashes. A decrease in the flash totals is seen beginning in August. However, similar to the values for the OTD flashes, the totals for November and December were greater than October. The minimum value for NLDN flashes was found in January. From January the totals increase each month except for May, which had a slight decrease, until the maximum is recorded in June. Presumably July begins the downward trend.

The IC lightning flashes listed in line 3 of Table 3 are derived from the difference between the OTD and the NLDN lightning flashes. The pattern in the monthly totals for the IC lightning flashes mirrors that of the OTD and NLDN monthly flash totals.

Figure 14 show the monthly totals for the OTD, the NLDN, and the derived IC lightning flashes on one graph. This figure clearly shows how the totals of the three groups of lightning compare to each other. For each month the OTD flashes had the largest totals. The IC totals were greater than the NLDN totals for all of the months.

Figure 15 shows the OTD and NLDN flashes collected for each month plotted against each other. The line of best fit was determined to have an intercept of -172.54 and slope of 0.38. The $r^2 = 0.96$ in this case shows the higher correlation between the OTD and NLDN flashes when they were grouped by month.

The monthly OTD data were plotted against the IC data and are shown shows a very higher correlation between in Figure 16. The $r^2 = 0.98$,

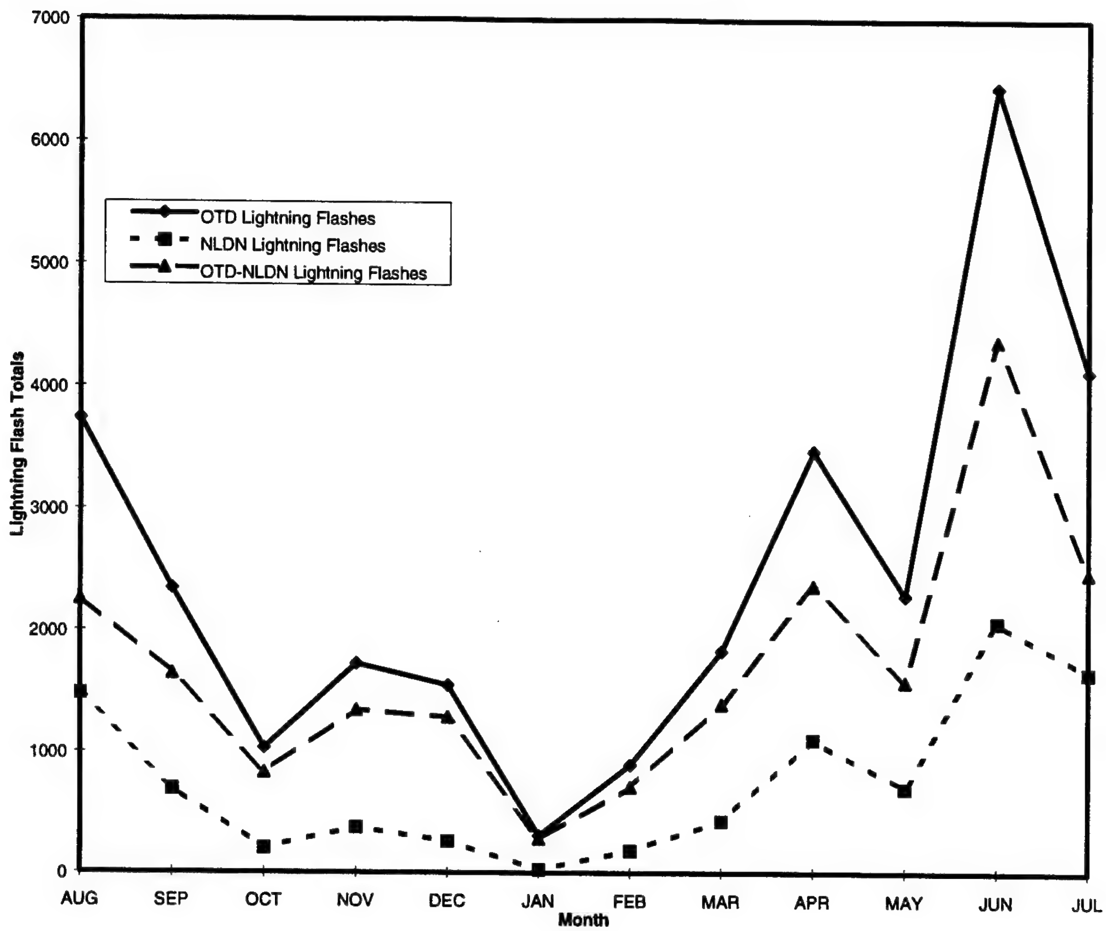


Figure 14. Comparison of Monthly OTD, NLDN, and OTD-NLDN Lightning Flash Totals

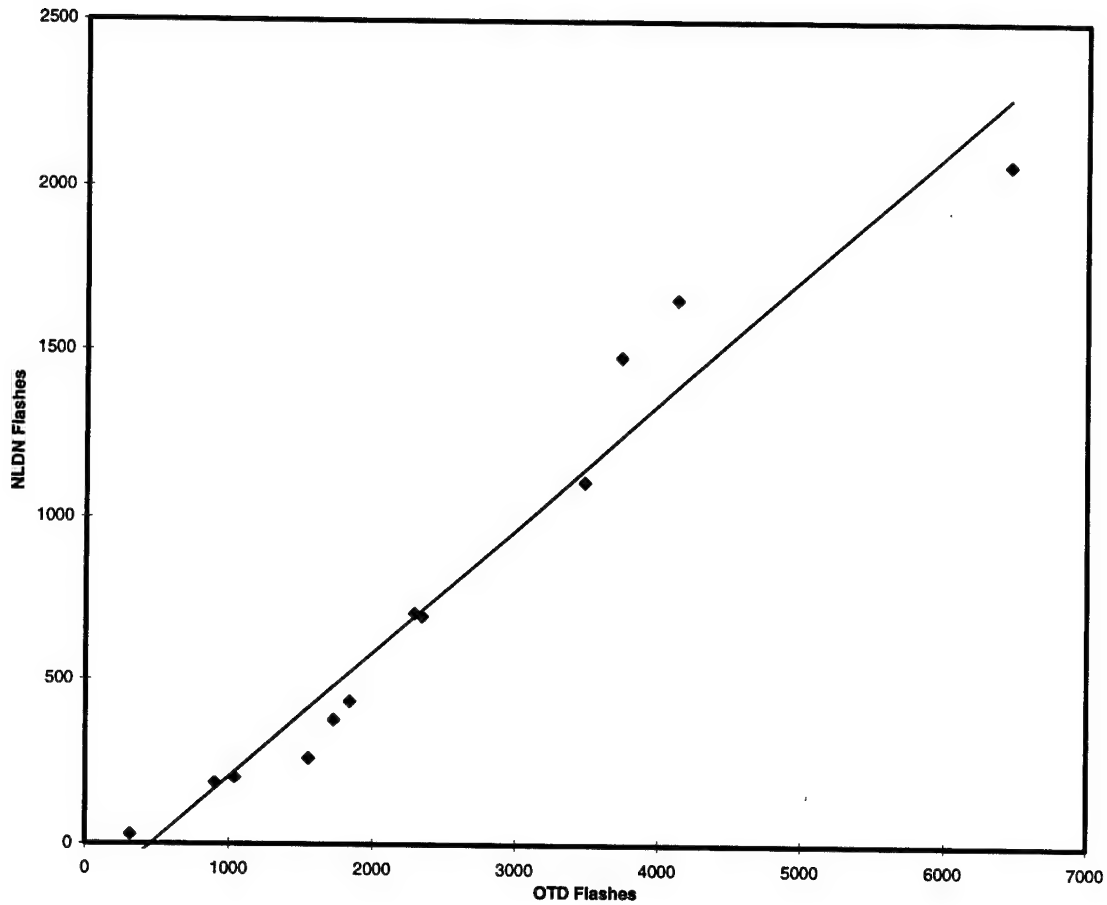


Figure 15. Monthly OTD Versus NLDN Lightning Flashes

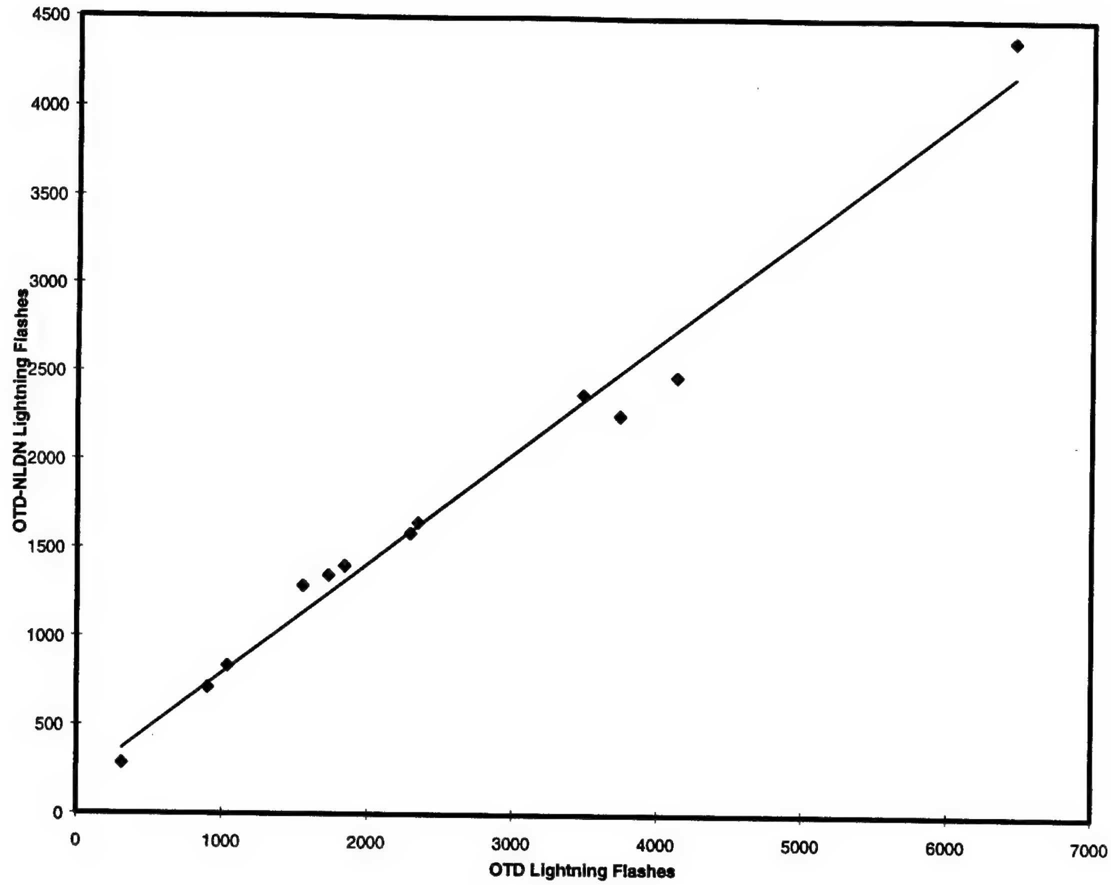


Figure 16. Monthly OTD Versus OTD-NLDN Lightning Flashes

the OTD and the IC lightning flashes when they are grouped by month. The intercept and slope of the line of best fit were 172.55 and 0.62 respectively.

To examine the relationship of the OTD flashes to the IC/CG by month, the values were computed and plotted in Figure 17. A negative relationship was evident in the figure. The intercept was 5.72. The coefficient of determination with $r^2 = 0.43$ indicated approximately 43% of the variation in the IC/CG ratio related to the monthly OTD lightning flash totals.

The plot of monthly NLDN flashes versus IC flashes is shown in Figure 18. The coefficient of determination in this case was also higher when the data were grouped by month. The $r^2 = 0.89$ the slope of the line of best fit was 1.52 and the intercept was 547.20.

Using the NLDN lightning flashes as representative of the CG lightning flashes and the OTD lightning flashes as representative of both the IC and CG lightning flashes, the percentage of CG lightning flashes of the total lightning flashes was computed and is listed in Table 3. Figure 19 shows the graph of the percentage of CG lightning flashes and the number of flash groups from which the monthly totals were compiled, plotted with a solid line. Using the flash totals for the entire year, the raw average of CG flashes was found to be approximately 31% of the total lightning detected by the OTD satellite with the adjusted percentage between 17 and 24% (Table 4). The 31% value is shown in Figure 19 with the horizontal line.

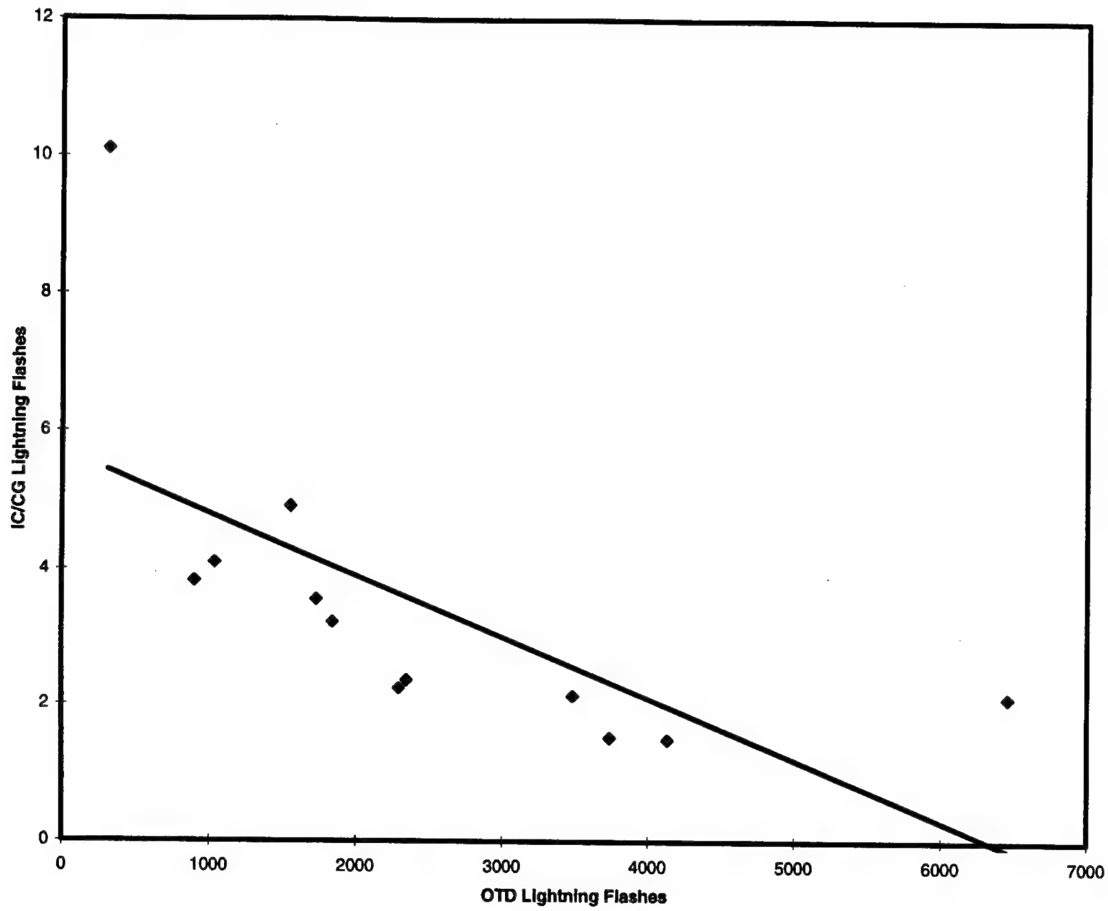


Figure 17. Monthly OTD Versus IC/CG Lightning Flashes (IC Flashes Derived from a Difference of OTD-NLDN Lightning Flashes)

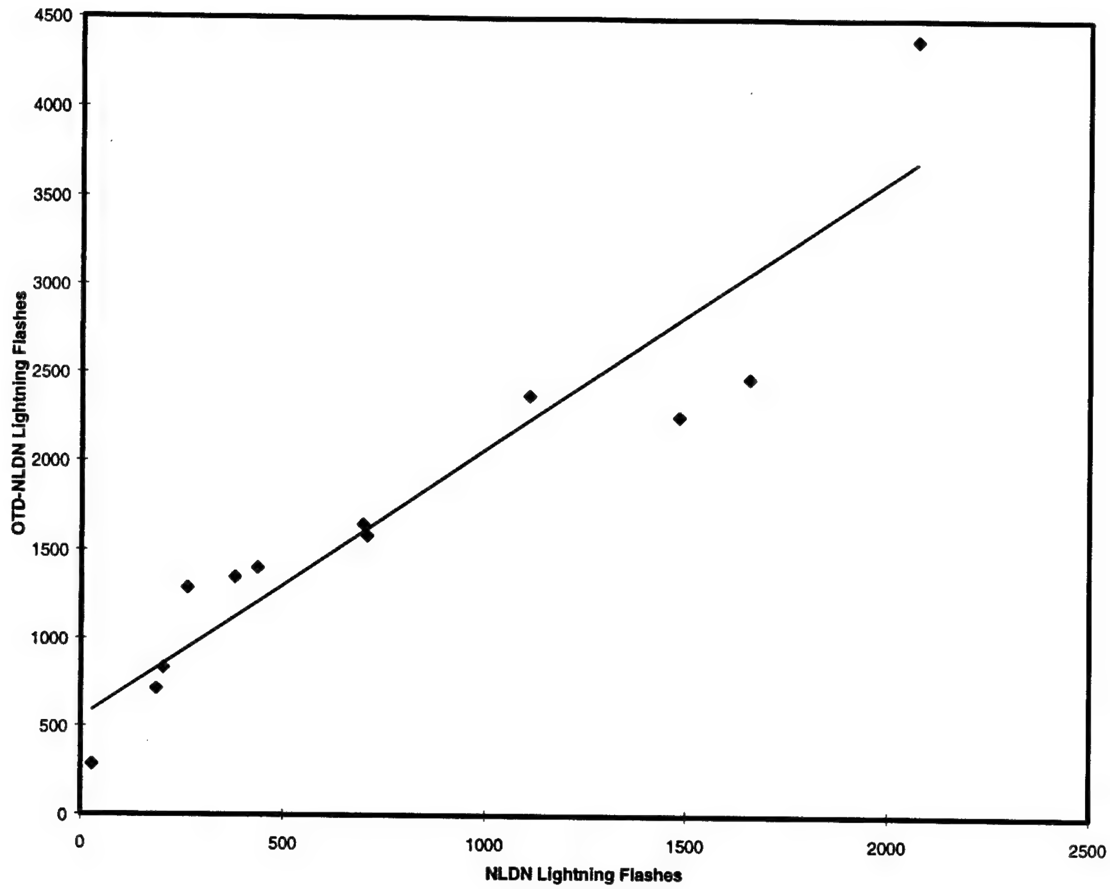
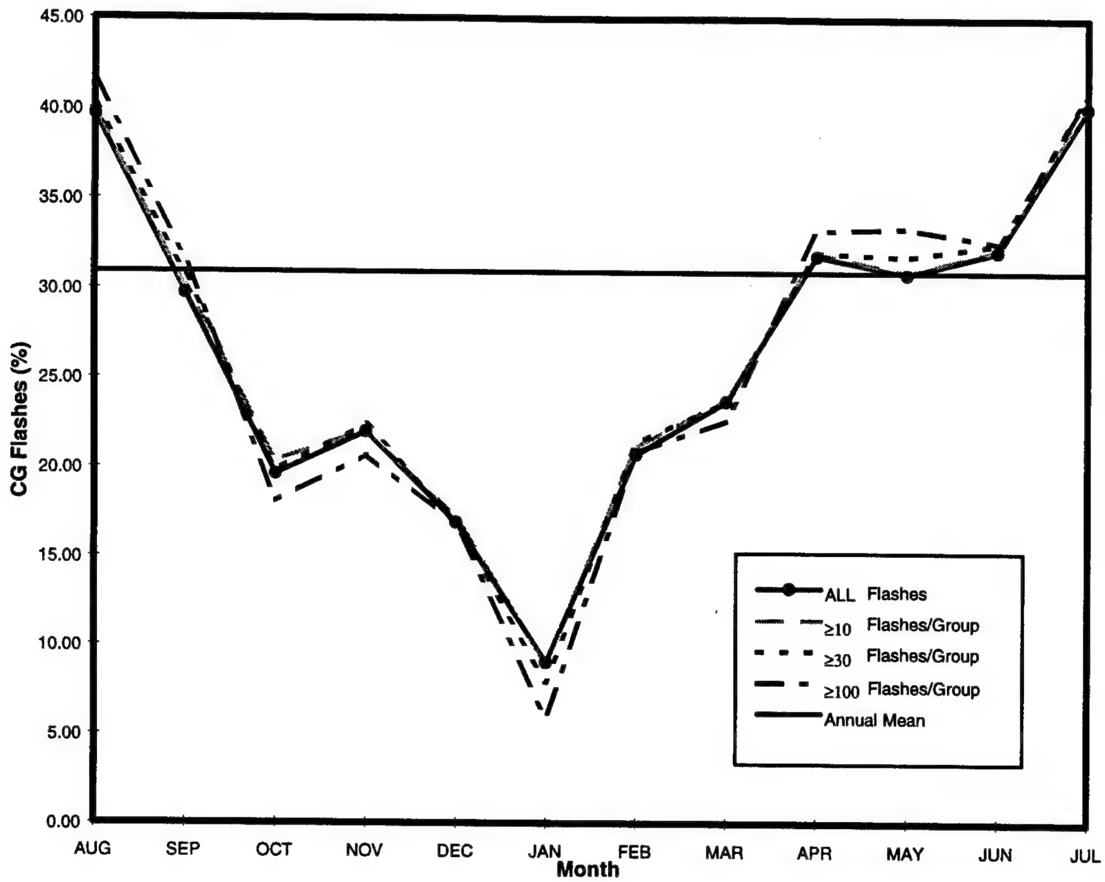


Figure 18. Monthly NLDN Versus OTD-NLDN Lightning Flashes



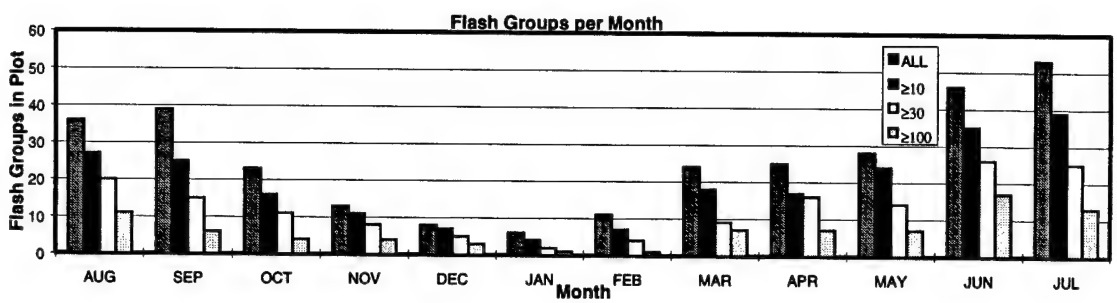


Figure 19. CG Lightning Flashes as a Percentage of Total Lightning Flashes Observed by the OTD Satellite and Flash Groups per Month

To examine the possibility of low numbers of lightning flashes skewing the results, the lightning flash data were filtered according to the number of OTD flashes in a group. The first filter eliminated groups of less than 10 OTD and the corresponding flashes. This is shown in Figure 19 with the dashed line. A filter was applied to eliminate the groups of less than 30 OTD and the corresponding NLDN flashes. This is shown in Figure 19 with a dotted line. This also produced similar results compared to the results including all of the flash data. The results of filtering the groups with less than 100 OTD and the corresponding NLDN flashes is shown with a dashed dotted line. The results of this filter begin to diverge from those of the other data sets primarily because the sample size in each month began to become too small. Figure 20 shows the percentage of CG flashes for each month from the groups of OTD flashes having at least 30 flashes in the group. The vertical lines represent the range of the percentage of CG flashes of the groups for each month. When all the groups of flashes for each month were used the range was often from 0 to 100%. This would be the result from an entire group of a low number of OTD flashes, possibly only one flash, either having or not having a corresponding NLDN flash. Figure 20 shows the variability that existed between the flash groups having at least 30 flashes in the group.

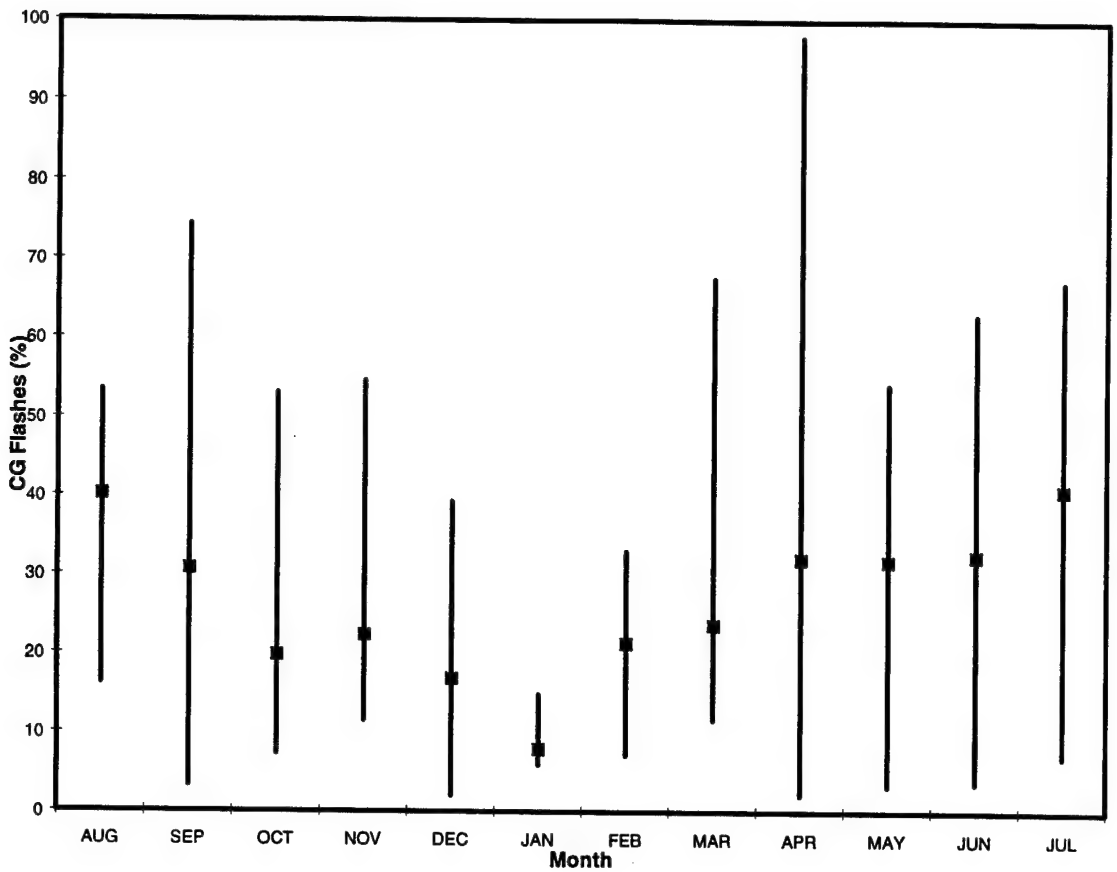


Figure 20. Monthly Percentage and Range of CG Lightning Flashes as a Percentage of Total Lightning Flashes Observed by the OTD Satellite of Flash Groups of at Least 30 Flashes

2.1. CG Lightning Flash Characteristics

Table 3 lists the percent positive of CG flashes for each month. August had the smallest value (8.23%) of all the months of this study. Figure 21 shows a plot of the values for each month. A trend of increasing percentage of positive CG flashes continued through December which had the largest value (27.86%). These results are similar to results found by Orville and Silver [1997]. From the peak in December, the trend was for generally decreasing values. The values for March, May, and June were against the trend, but the trend for these three months also showed a decrease.

The mean negative multiplicity for the CG lightning flashes is listed in Table 3. Figure 22 shows a plot of the monthly mean negative multiplicity. The minimum value occurred in February. The lowest values occurred in the months of October, January, February, and March. The maximum value occurred in September. The highest values occurred in the months of September, May, June, and July. Generally, the mean negative multiplicity was higher in the summer months and lower in the winter months.

The positive mean peak current is listed in Table 3. Figure 23 shows the plots of the positive mean peak current for each month of the study. In August the value was 16.9 kA. The value for September was slightly higher but then it took a dramatic jump in October to peak at 44.92 kA. Then the

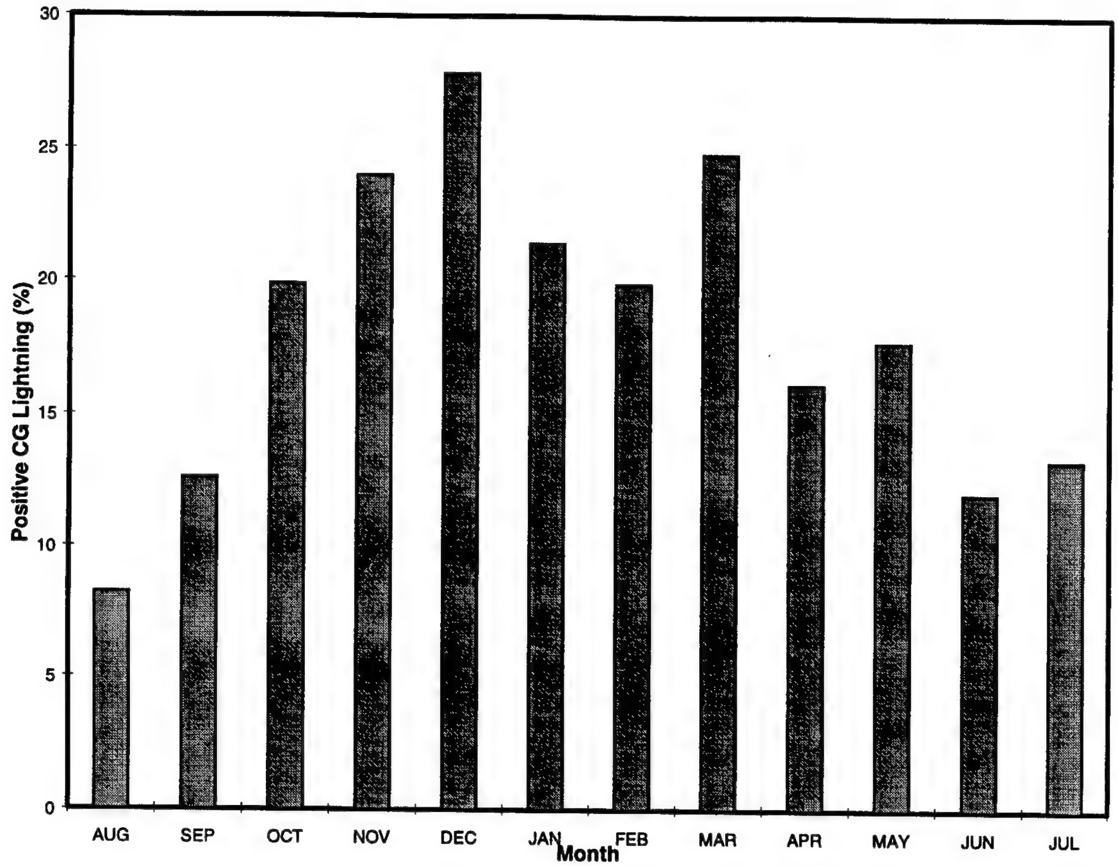


Figure 21. Monthly Percentage of Positive CG Lightning Flashes

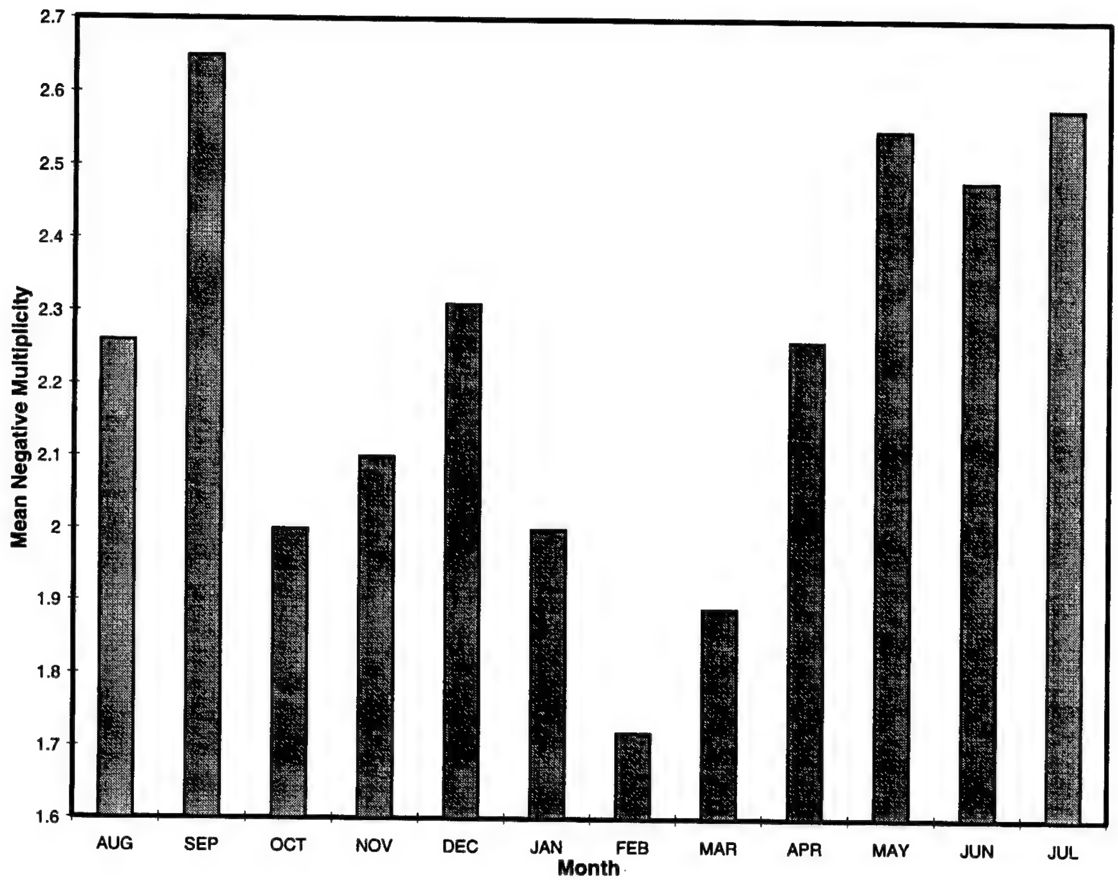


Figure 22. Monthly Mean Negative Multiplicity of CG Lightning Flashes

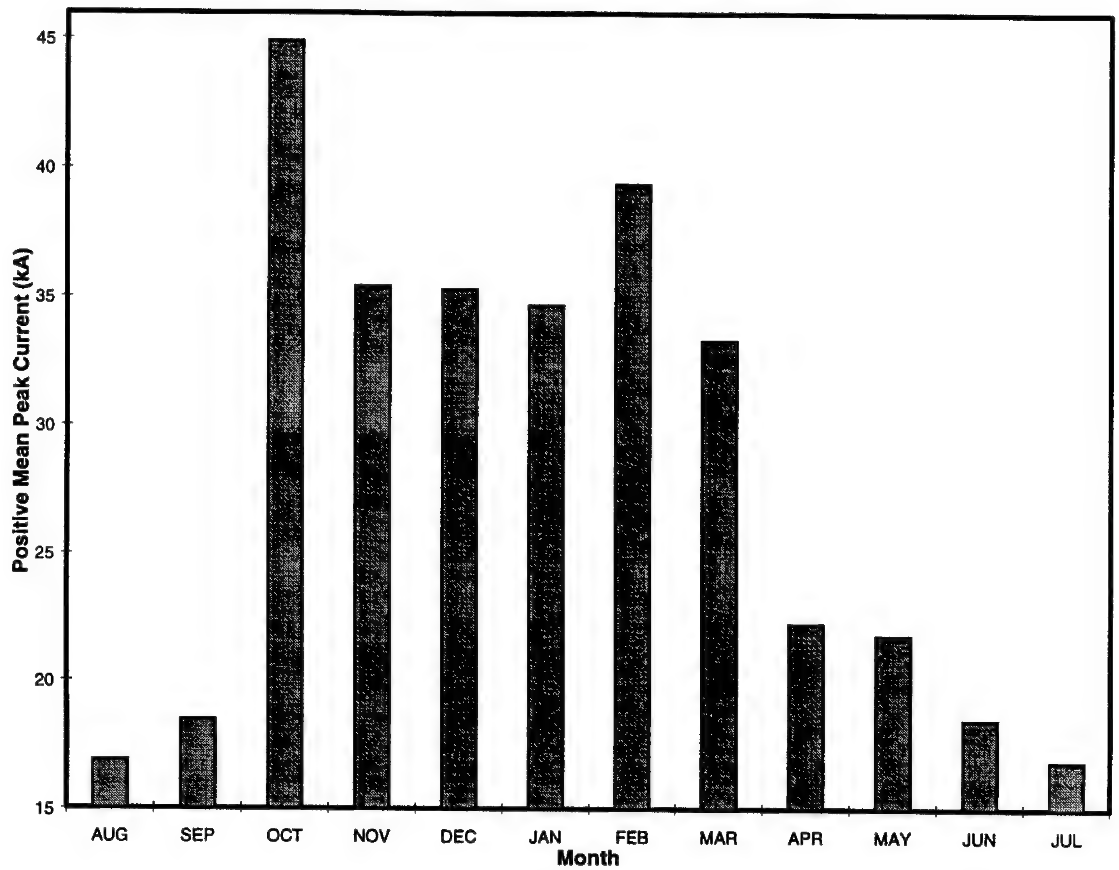


Figure 23. Monthly Positive Mean Peak Current of CG Lightning Flashes

values dropped to approximately 35 kA where they remained through March except for February which was nearly 40 kA. The values then dropped in April to 22.23 kA and then gradually decreased to the minimum value in July of 16.87 kA.

The monthly negative mean peak current is listed in Table 3. The values are plotted in Figure 24. The negative mean peak current for August 30.7 kA. Similar to that of the positive mean peak current, the value for September was slightly higher than August then jumped to 40.27 kA for October. Unlike the behavior of the values for the positive mean peak current which remained high through March, the value for November dropped to a value less than that of August (30.53 kA). The value for December exceeded the value for October and the currents remained relatively high through March although more variable than those of the positive mean peak currents. The negative mean peak current dropped to 27.54 kA in April and to the minimum value of 26.64 kA in May. The value for June equaled that of August and was slightly lower in July. Generally the negative mean peak current was higher in the winter months than in the summer months as was the case for the positive mean peak currents.

3. IC and CG Lightning Flash Characteristics Comparison

The percentage of the monthly IC lightning flash percentage and the percentage of positive CG lightning flashes was determined to have an r^2 =

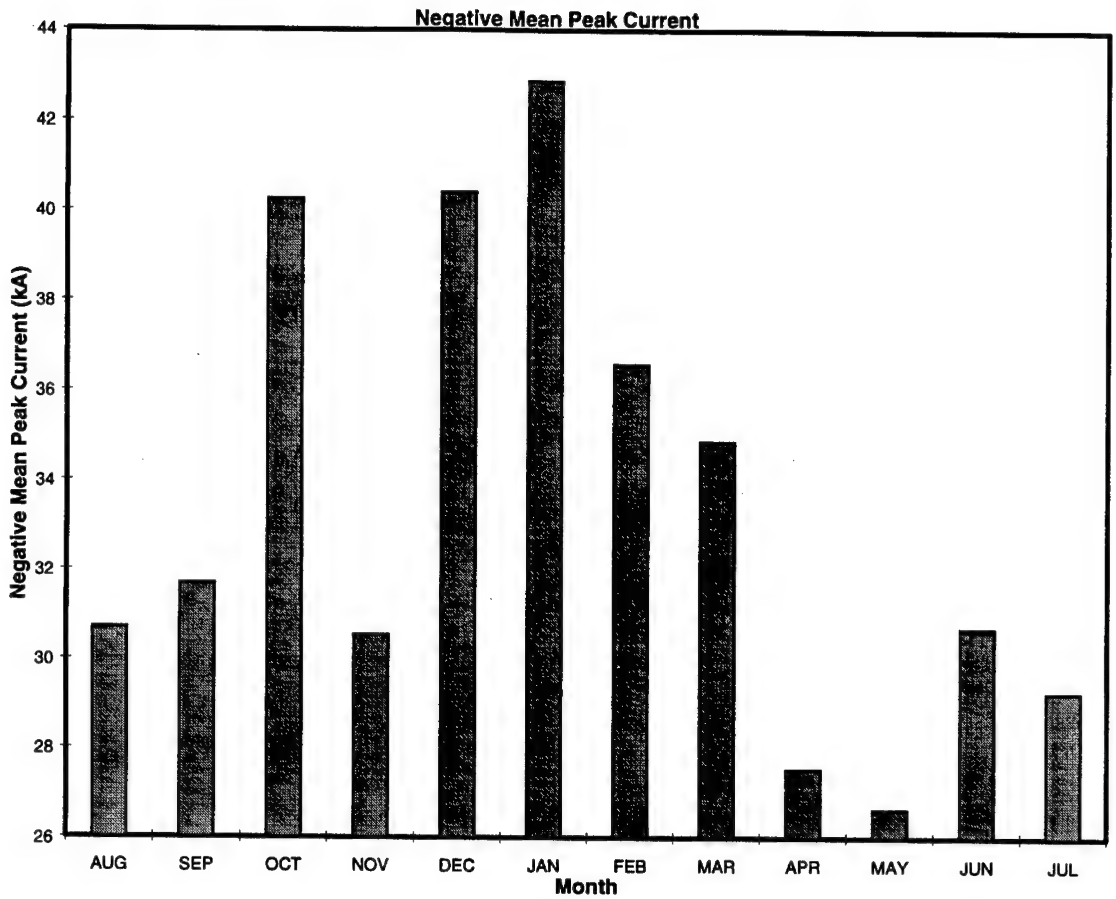


Figure 24. Monthly Negative Mean Peak Current of CG Lightning Flashes

0.63. The plot of the data is shown in Figure 25. The slope of the line of best fit was 0.50 and the intercept was -18.76.

To examine the relationship of the monthly IC lightning flash percentage to the mean negative multiplicity of the CG flashes, the values were computed and plotted in Figure 26. The intercept of the line of best fit was 3.68. A negative relationship is evident with the slope of the line of best fit of -0.02. The coefficient of determination equal to 0.38 indicated approximately 38% of the variation in the mean negative multiplicity of the CG flashes related to the monthly IC lightning flash percentage.

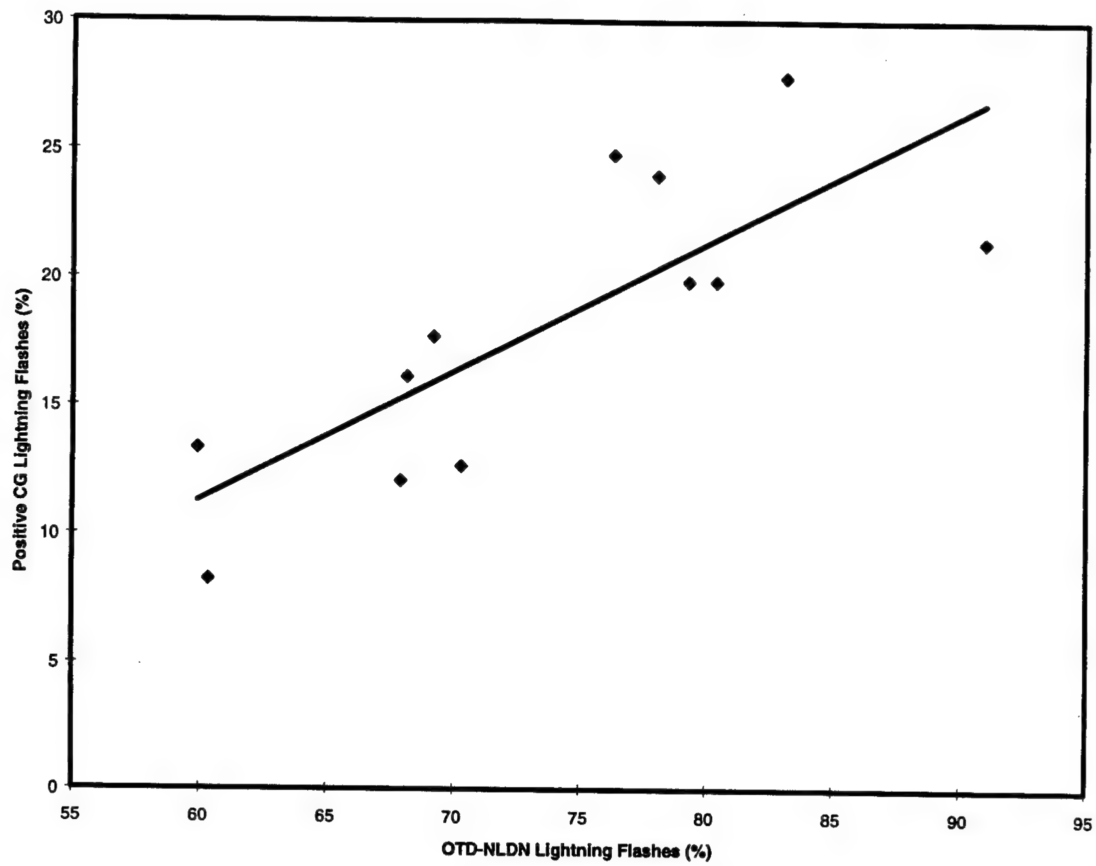


Figure 25. Monthly Percentage of OTD-NLDN Lightning Flashes Versus Percentage of Positive CG Lightning Flashes

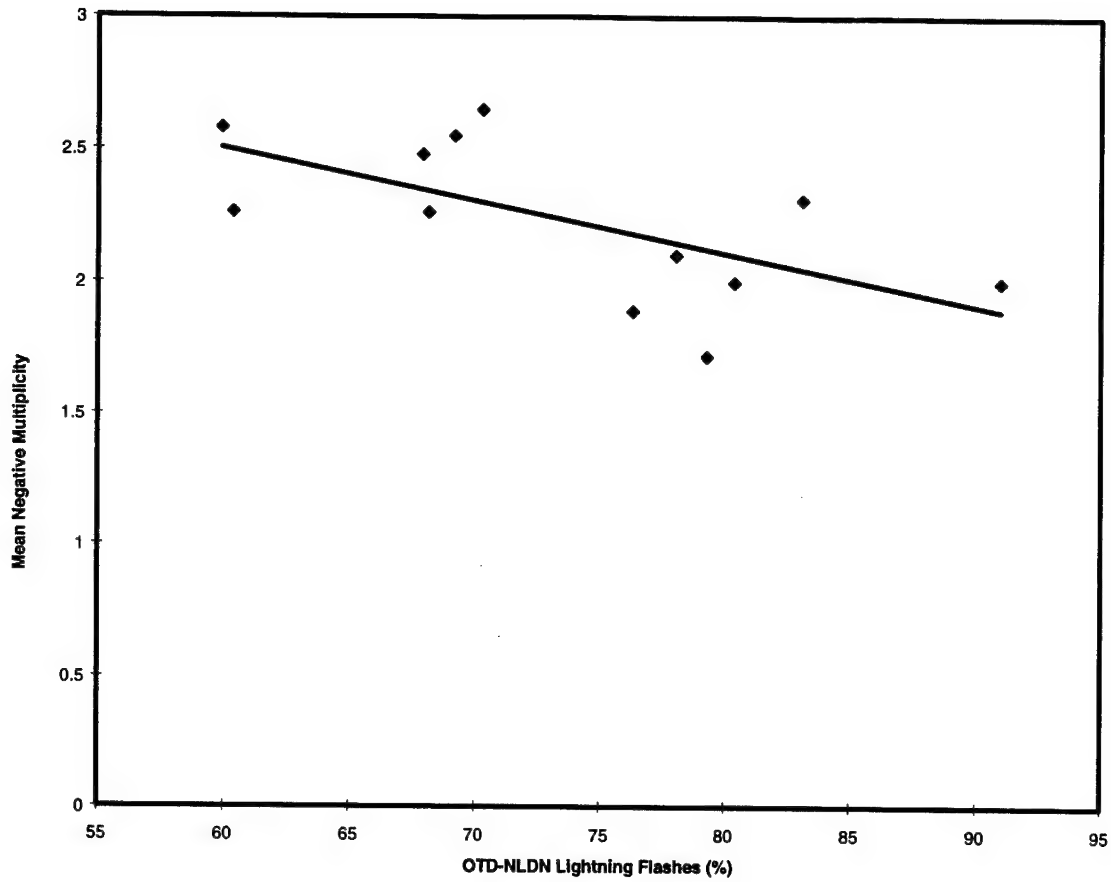


Figure 26. Monthly Percentage of OTD-NLDN Lightning Flashes Versus Mean Negative Multiplicity of CG Lightning Flashes

CHAPTER IV

DISCUSSION

1. Lightning Flash Data

The total number of OTD flashes recorded in the region of interest for this study was 29,808. This is assumed to be 56% ±10% of the actual number of lightning flashes that occurred during the satellite overpasses of the region of interest based on the estimated detection efficiency of the OTD satellite. The total number of coincident NLDN lightning flashes collected during this study was 9214. This resulted in a derived total of IC lightning flashes of 20,594. The computed percentage of CG lightning flashes was 30.91% for the entire year. These figures were not adjusted for the detection efficiency of the NLDN which has been estimated at 70% [Orville, 1991a, 1991b, 1994; Orville and Silver, 1997] or even as high as 80 to 90% [Cummins et al., 1998].

With an estimated detection efficiency of 56% ±10% for the OTD the actual number of lightning flashes in the region of interest may been between 45,309 and 64,683 for the period of study. With an assumed detection efficiency of 85% for the NLDN, the actual number of CG lightning flashes may have been 10,872 adjusting for the detection efficiency of the NLDN alone. It is considered that this number would likely have been even

larger since more CG lightning flashes would have been collocated with the additional OTD lightning flashes. Using the figures adjusted for the detection efficiency, the computed percentage of CG lightning flashes was between 17-24%, as compared to the raw value of about 31%. In either case, the CG flashes were found to be a minority of the total lightning flashes.

The totals of monthly OTD and NLDN lightning flashes showed a general trend of decreasing numbers of flashes each month from August to the minimum value detected in January. This trend follows what would be expected with the seasonal characteristics of thunderstorms in the region of interest. The percentage of CG lightning flashes generally followed the trend of the total number of OTD lightning flashes as shown in Figure 27. Although the lightning flash numbers generally increase each month from January and reach their peak in June, the percentage of CG flashes for this study was found to peak in July, with the percentage of CG lightning flashes for August nearly as high. However, January had both the minimum numbers of flashes detected and the minimum percentage of CG flashes.

The majority of lightning was detected in the months of August, April, May, June, and July. The percentage of CG lightning for these 5 months was above the percentage for the year except for May which was only slightly below the percentage for the year.

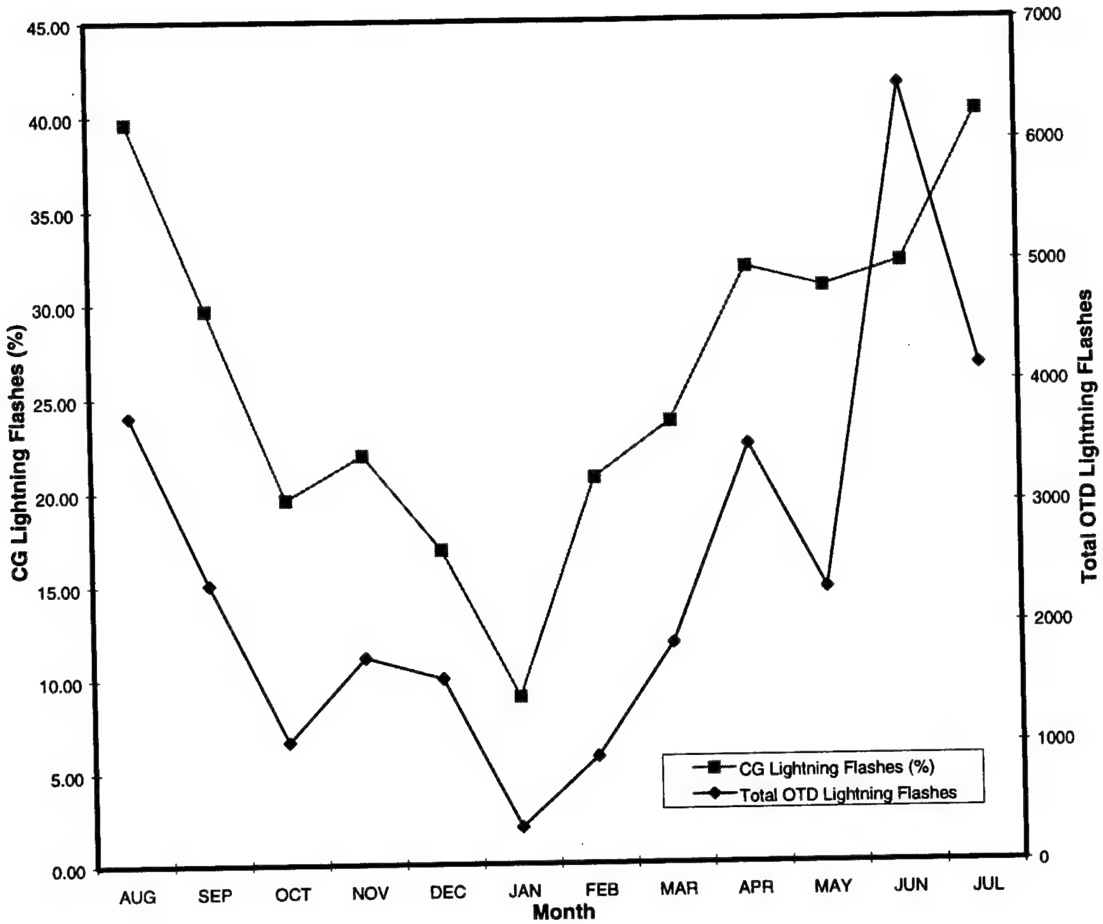


Figure 27. Monthly Percentage of CG Flashes and Total OTD Lightning Flashes

Throughout the year period of this study, the fall, winter, and early spring months had the lowest percentage of CG lightning flashes (or the highest percentage of IC lightning flashes).

2. CG Lightning Flash Characteristics

The monthly percentage of positive CG lightning flashes showed a similar trend compared to results of Orville and Silver [1997]. The 1995 data used for this study were from a much smaller region than the area used in their study and the data were collected only when the OTD satellite detected lightning, resulting in as few as 0.03% of the total monthly number of CG flashes as used in their study. The minimum percentage of positive CG lightning was found in August and the maximum was found in December.

The mean negative multiplicity was shown to have a minimum in the winter months and higher values generally occurred in the summer months. The maximum for this study was found to be 2.65 in September. The minimum value was 1.72 in February.

The positive mean peak current was shown to be higher from October through March. The values were low during August and September before increasing by almost 3 times. The positive mean peak current decreased by approximately 1/3 from March to April. The minimum values were found

from June through September. These results were in agreement with those found by Silver [1995].

The variability of the negative mean peak current was greater than observed for the positive mean peak current. A general trend of higher negative mean peak currents in the winter and lower peak currents in the spring and summer was found. Unlike the positive mean peak current, the lowest values were found in April and May, although August and July were equal to or lower than the remaining monthly values. The general trend of the negative mean peak current was in agreement with the results found by Silver [1995].

3. IC and CG Lightning Flash Characteristics Comparison

Figure 28 shows the relationship between the monthly OTD lightning flashes and the IC/CG lightning flash ratio. The regression analysis for these parameters was performed in the preceding chapter. This figure shows as the monthly total of OTD flashes decreased from summer to winter during this study, the trend of IC/CG ratio was generally opposite. As the OTD flash monthly flash totals increased from winter to summer, the trend of IC/CG flashes generally increased.

To show the relationship between the percentage of positive CG lightning flashes and the percentage of IC lightning flashes, both parameters were plotted and shown in Figure 29. The regression analysis

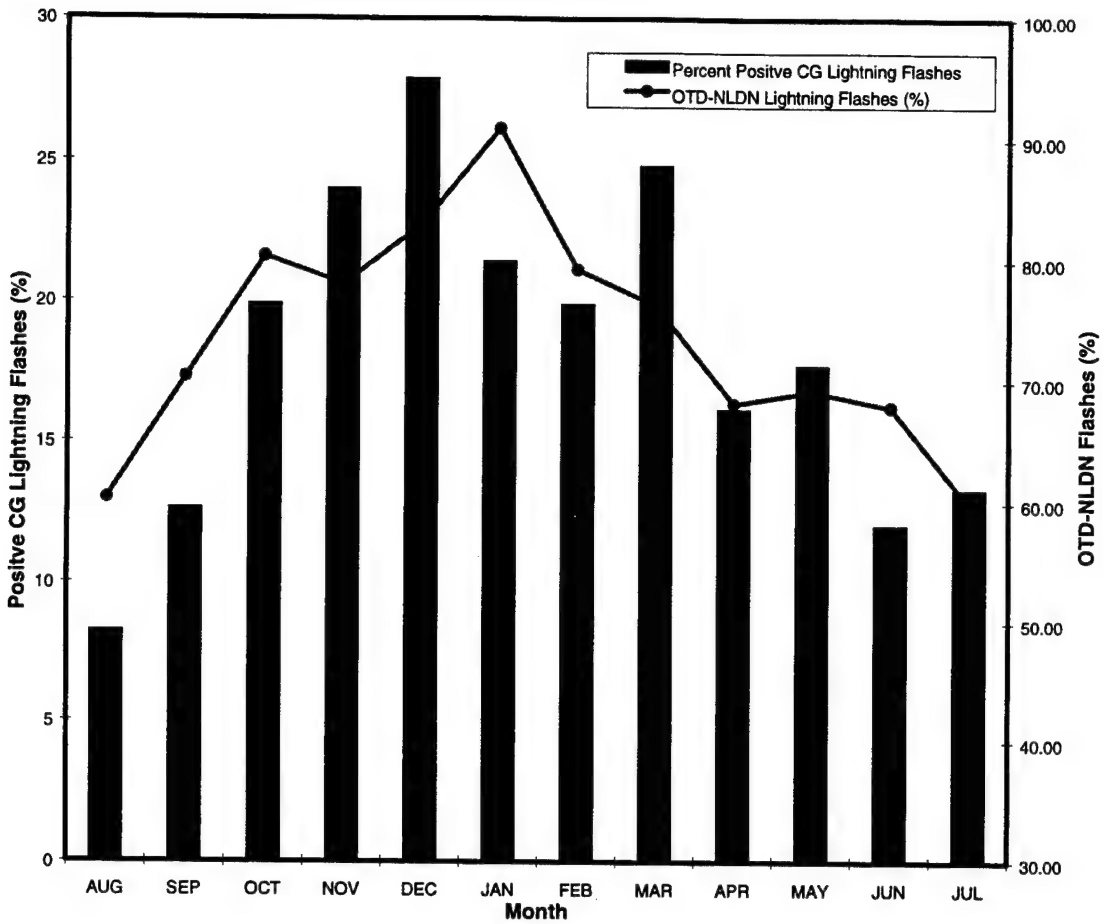


Figure 29. Monthly Percent Positive CG Flashes and Percent OTD-NLDN Lightning Flashes

was performed in the preceding chapter. This figure shows as the percentage of IC lightning flashes increases, the percentage of positive CG lightning flashes generally increases as well. The percentage of positive CG lightning flashes is lowest in the summer months as is the percentage of IC lightning flashes. The percentage of positive CG lightning flashes is at a maximum in the winter months with December having the highest percentage and the percentage of IC lightning flashes is also at a maximum in the winter with the highest value found in January.

The relationship between the mean negative multiplicity of the CG lightning flashes and the percentage of IC lightning flashes is shown in Figure 30. Although the relationship between the mean negative multiplicity of the CG flashes and the percentage of IC lightning flashes is not as strong as the relationship between the percentage of positive CG lightning flashes and the percentage of IC lightning flashes, it can be seen in the figure that as the maximum values of mean negative multiplicity occurred in the summer and early fall, that this is when the minimum percentages of IC lightning were found. The minimum value for the mean negative multiplicity occurred in the winter while the highest percentage of IC flashes were found during the winter.

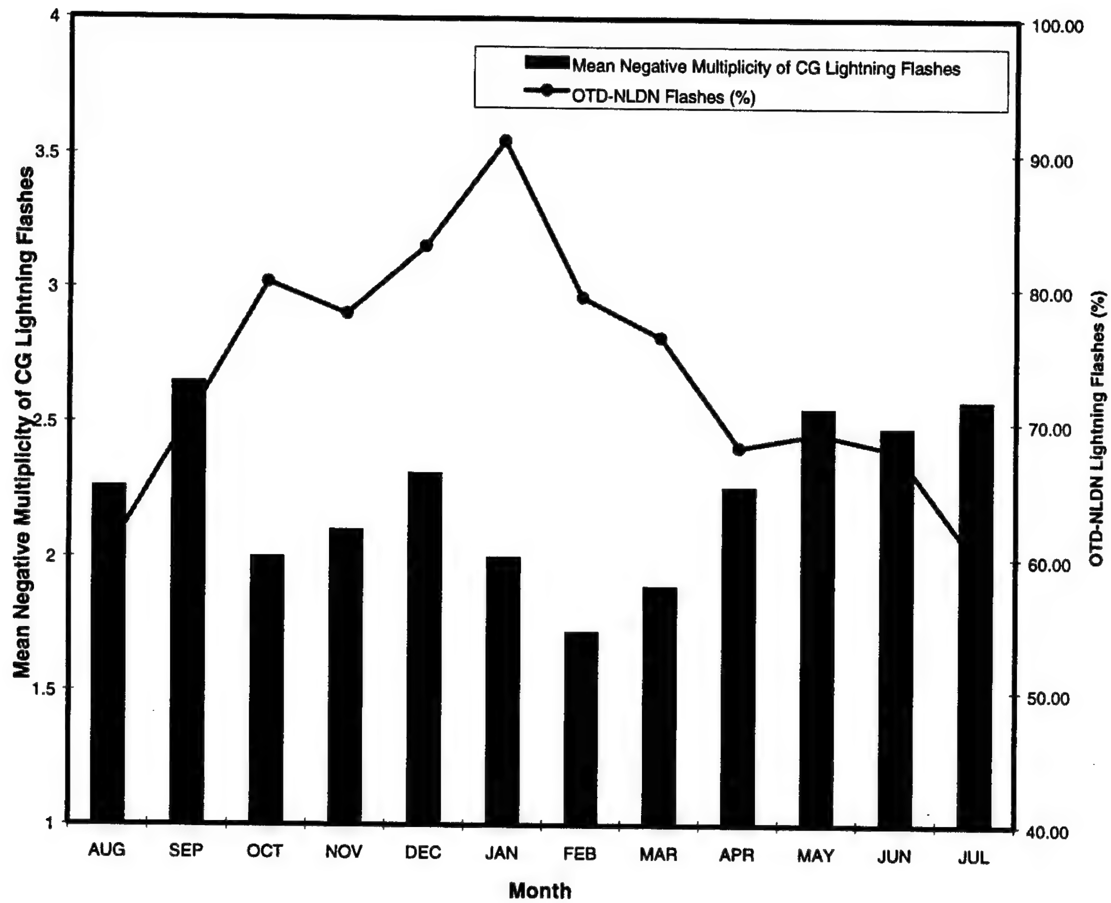


Figure 30. Monthly Mean Negative Multiplicity of CG Flashes and Percent OTD-NLDN Lightning Flashes

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

As stated earlier, the goal of this research was to demonstrate the feasibility of using total lightning flash (IC and CG) collected from the OTD satellite in conjunction with CG lightning flashes recorded by the NLDN so as to derive separately the IC and CG lightning activity in the region of interest. These data were then used to examine a possible seasonal relationship of the IC lightning to CG lightning flash data and of the percent positive and negative multiplicity of the lightning data detected by the NLDN.

1. Conclusions

Several conclusions were determined from the results of this research. They are in the order of the objectives on page 11 as follows:

1. Although the lightning data were readily available in the region of interest for this study, one of the drawbacks of using the OTD lightning flash data was the locational errors present. These errors necessitated using a time and area determined method of collocating the lightning flashes detected by the OTD satellite and the NLDN. The result of employing this

method both excluded some of the NLDN flashes from the data that should have been included as well as included some of the NLDN flashes that should have been excluded. It was considered that the collocation procedure did not seriously affect the results of this study.

2. The lightning flashes detected by the OTD satellite were positively correlated with the lightning flashes detected by the NLDN. This would be expected since as the storms produce more CG lightning, the OTD satellite would be detecting an increase in lightning activity.

Despite the problems with determining the lightning flashes occurring synchronously with each other, this study was able to determine the IC lightning occurring in the region of the study. The overall unadjusted IC/CG ratio for this study was found to be 2.23. When the figures were adjusted for the detection efficiency of 56% ±10% for the OTD and 85% for the NLDN, the ratio was between 3.17-4.95. It is difficult to draw a conclusion about the IC/CG ratio for the year when the ratio varies by an order of 2.5 from approximately 2 to 5. In order to remedy this the estimate of the detection efficiency must be determined with greater certainty and the overall detection efficiency of a space based lightning detection system must be improved. However, this does not alter the conclusions that can be drawn about the trends of the monthly and seasonal variation of the IC/CG ratio.

It was found that IC/CG ratio was higher in the winter months (greater than 10 in January with the adjusted values between 13 and 19) than in the summer months (approximately 1.5 in July and August with the adjusted values between 2.2 and 3.6) generally opposite to the behavior of the lightning flashes detected by the OTD or the NLDN. For this study it was concluded that as the lightning flashes decreased from summer to winter, the ratio of IC/CG lightning generally increased and as the lightning flashes increased from winter to summer, the ratio of IC/CG lightning generally decreased.

3. The monthly percentage of positive CG lightning generally followed the monthly percentage of IC lightning during the year. As the percentage of positive of CG flashes increased from the summer months to the winter, the percentage of IC flashes also increased, and as the percentage of positive CG flashes decreased from winter to summer, the percentage of IC flashes also decreased. This suggests the winter storm systems with their lower freezing levels and the lower cloud tops result in more IC discharges per CG discharges and when CG discharges do occur they were more likely to deliver a positive charge to ground.

4. The monthly mean negative multiplicity was negatively correlated with the monthly percentage of IC flashes. The monthly mean negative multiplicity generally decreased from the summer to the winter as the

percentage of IC lightning flashes increased. From the winter months to the summer months, the monthly mean negative multiplicity increased while the same percentage of IC lightning flashes decreased. The decrease in mean negative multiplicity could be attributed again to storm structure. As winter approaches the storms do not grow as high as they do in the warmer months due to the weaker up drafts. This may play a role in both fewer strokes to ground per lightning flashes as well as fewer CG flashes resulting in higher percentage of IC lightning flashes.

2. Recommendations

This research has shown the results of using the OTD satellite data to determine the amount IC lightning and the NLDN to determined the amount of CG lightning in the region of interest for a period of one year. Areas where this research can be extended are:

1. The entire collection of OTD lightning flash data could be used to investigate yearly differences and develop a larger data set.
2. The study could be expanded to include the entire continental United States and perhaps examine lightning differences by region.
3. A more refined algorithm could be used to collocate the lightning flashes collected by the OTD satellite and the NLDN.
4. Data from the TRMM satellite could be used to study lightning in the

region of interest.

5. A study could be restricted to the land. This would prevent the decreased detection efficiency of the NLDN skewing the results if a comparison were performed.

6. A study be performed to detect a difference in the IC and CG lightning activity between the land and over the water.

7. A relationship between storm type and IC/CG ratios could be examined.

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APPENDIX A

MONTHLY RAW LIGHTNING FLASH DATA

Table A1. OTD and NLDN Lightning Flash Data for September

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
0	244	9/1/95	22	2	20	9.09	0.00	2.0	0.0	-57.5
8	244	9/1/95	6	1	5	16.67	0.00	3.0	0.0	-21.6
9	244	9/1/95	31	1	30	3.23	0.00	4.0	0.0	-26.2
8	245	9/2/95	20	4	16	20.00	0.00	2.0	0.0	-39.7
99	246	9/3/95	3	0	3	0.00	.	.	.	.
99	248	9/5/95	84	15	69	17.86	20.00	2.2	22.0	-40.7
8	248	9/5/95	79	10	69	12.66	0.00	1.3	0.0	-32.6
99	249	9/6/95	17	1	16	5.88	0.00	3.0	0.0	-51.9
0	249	9/6/95	18	1	17	5.56	100.00	0.0	10.7	0.0
99	250	9/7/95	55	4	51	7.27	0.00	1.5	0.0	-28.2
7	250	9/7/95	5	0	5	0.00	.	.	.	.
8	250	9/7/95	7	1	6	14.29	0.00	1.0	0.0	-12.3
99	251	9/8/95	116	17	99	14.66	5.88	2.2	46.2	-30.3
1	251	9/8/95	68	46	22	67.65	6.52	3.2	15.7	-30.0
9	251	9/8/95	7	3	4	42.86	0.00	1.7	0.0	-39.4
14	251	9/8/95	1	0	1	0.00	.	.	.	.
7	252	9/9/95	2	0	2	0.00	.	.	.	.
7	253	9/10/95	3	0	3	0.00	.	.	.	.
99	256	9/13/95	147	42	105	28.57	4.76	2.7	48.2	-30.9
9	256	9/13/95	8	0	8	0.00	.	.	.	.
14	256	9/13/95	695	249	446	35.83	21.29	3.4	15.9	-31.0
7	257	9/14/95	5	1	4	20.00	0.00	1.0	0.0	-7.3
12	257	9/14/95	39	29	10	74.36	13.79	2.4	19.3	-31.6
1	258	9/15/95	2	0	2	0.00	.	.	.	.
7	258	9/15/95	159	43	116	27.04	0.00	1.8	0.0	-23.4
12	259	9/16/95	156	72	84	46.15	9.72	2.2	12.4	-28.8
12	260	9/17/95	28	10	18	35.71	0.00	2.8	0.0	-45.1
13	260	9/17/95	51	10	41	19.61	20.00	1.5	13.6	-45.9
7	262	9/19/95	54	31	23	57.41	22.58	2.5	32.1	-35.5
6	264	9/21/95	1	0	1	0.00	.	.	.	.
11	264	9/21/95	1	1	0	100.00	0.00	2.0	0.0	-51.9
1	266	9/23/95	263	62	201	23.57	4.84	2.2	15.7	-28.6
6	267	9/24/95	7	4	3	57.14	0.00	1.8	0.0	-97.2
12	267	9/24/95	12	3	9	25.00	0.00	2.0	0.0	-53.1
11	268	9/25/95	1	0	1	0.00	.	.	.	.
5	269	9/26/95	18	9	9	50.00	22.22	2.9	27.7	-55.7
10	270	9/27/95	13	1	12	0.00	7.69	1.0	0.0	-31.7
5	271	9/28/95	23	3	20	0.00	13.04	1.0	0.0	-33.5
6	271	9/28/95	21	10	11	47.62	0.00	2.6	0.0	-25.6
11	271	9/28/95	87	9	78	10.34	0.00	2.2	0.0	-34.4
5	272	9/29/95	7	0	7	0.00	.	.	.	.
9	273	9/30/95	2	1	1	50.00	0.00	1.0	0.0	-27.0
		TOTAL	2344	696	1648	29.69				
		MEAN	55.81	16.57	39.24		12.64	2.65	18.49	-31.69

Table A2. OTD and NLDN Lightning Flash Data for October

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
11	274	10/1/95	101	9	92	8.91	11.11	1.6	5.9	-53.1
5	275	10/2/95	30	6	24	20.00	0.00	1.3	0.0	-48.6
10	275	10/2/95	78	10	68	12.82	0.00	2.5	0.0	-33.6
11	275	10/2/95	6	0	6	0.00	.	.	.	.
5	276	10/3/95	8	0	8	0.00	.	.	.	.
11	276	10/3/95	1	0	1	0.00	.	.	.	.
4	277	10/4/95	5	0	5	0.00	.	.	.	.
10	277	10/4/95	58	6	52	10.34	0.00	3.2	0.0	-71.3
4	278	10/5/95	5	0	5	0.00	.	.	.	.
10	278	10/5/95	10	2	8	20.00	0.00	2.0	0.0	-34.5
10	279	10/6/95	2	0	2	0.00	.	.	.	.
4	280	10/7/95	20	3	17	15.00	66.67	2.0	33.5	-19.8
9	280	10/7/95	1	0	1	0.00	.	.	.	.
10	283	10/10/95	5	0	5	0.00	.	.	.	.
3	284	10/11/95	2	0	2	0.00	.	.	.	.
9	284	10/11/95	19	3	16	15.79	0.00	1.0	0.0	-28.5
4	287	10/14/95	2	1	1	50.00	0.00	1.0	0.0	-27.0
10	287	10/14/95	30	4	26	13.33	25.00	1.0	85.2	-27.7
8	288	10/15/95	25	11	14	44.00	0.00	3.0	0.0	-60.0
8	293	10/20/95	39	4	35	10.26	25.00	1.0	19.1	-41.6
8	294	10/21/95	4	0	4	0.00	.	.	.	.
8	298	10/25/95	49	26	23	53.06	11.54	2.5	61.5	-46.5
7	299	10/26/95	11	3	8	27.27	0.00	1.3	0.0	-14.9
3	300	10/27/95	137	28	109	20.44	17.86	1.8	16.6	-22.2
8	300	10/27/95	187	56	131	29.95	26.79	2.1	54.2	-33.0
7	301	10/28/95	151	11	140	7.28	0.00	2.1	0.0	-38.2
8	301	10/28/95	49	20	29	40.82	0.00	1.2	0.0	-55.0
1	303	10/30/95	1	0	1	0.00	.	.	.	.
		TOTAL	1036	203	833	19.59				
		MEAN	37.00	7.25	29.75		13.79	2.01	44.92	-40.27

Table A3. OTD and NLDN Lightning Flash Data for November

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
6	305	11/1/95	310	82	228	26.45	39.02	2.1	27.7	-30.3
1	306	11/2/95	15	5	10	33.33	0.00	2.8	0.0	-18.4
6	306	11/2/95	255	87	168	34.12	31.03	2.1	21.2	-27.6
1	307	11/3/95	196	23	173	11.73	56.52	2.1	19.4	-36.9
6	307	11/3/95	1	0	1	0.00	.	.	.	.
6	311	11/7/95	66	36	30	54.55	5.56	2.9	32.2	-38.7
5	312	11/8/95	69	21	48	30.43	14.29	2.8	12.2	-35.3
7	314	11/10/95	2	0	2	0.00	.	.	.	.
5	315	11/11/95	620	93	527	15.00	4.30	1.7	82.9	-27.8
13	315	11/11/95	22	6	16	27.27	16.67	1.6	27.8	-45.1
5	316	11/12/95	20	0	20	0.00	.	.	.	.
4	319	11/15/95	1	0	1	0.00	.	.	.	.
99	322	11/18/95	17	3	14	17.65	66.67	1.0	55.8	-29.2
5	323	11/19/95	6	0	6	0.00	.	.	.	.
5	325	11/21/95	6	1	5	16.67	100.00	0.0	29.8	0.0
4	327	11/23/95	56	15	41	26.79	40.00	1.2	151.8	-18.6
3	328	11/24/95	2	1	1	50.00	0.00	3.0	0.0	-98.5
11	328	11/24/95	12	0	12	0.00	.	.	.	.
3	333	11/29/95	52	6	46	11.54	0.00	3.0	0.0	-36.0
		TOTAL	1728	379	1342	21.93				
		MEAN	90.95	19.95	71.00		24.01	2.10	35.42	-30.53

Table A4. OTD and NLDN Lightning Flash Data for December

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
2	341	12/7/95	4	0	4	0.00	.	.	.	.
1	343	12/9/95	21	7	14	33.33	14.29	1.7	22.8	-46.4
9	343	12/9/95	8	0	8	0.00	.	.	.	.
1	344	12/10/95	3	0	3	0.00	.	.	.	.
9	350	12/16/95	39	8	31	20.51	12.50	2.4	83.8	-57.8
1	351	12/17/95	18	3	15	16.67	66.67	1.0	67.5	-27.8
9	351	12/17/95	257	101	156	39.30	24.75	2.2	43.2	-39.8
0	352	12/18/95	519	116	403	22.35	34.48	2.6	29.3	-40.9
8	352	12/18/95	94	15	79	15.96	20.00	2.4	21.0	-28.6
0	354	12/20/95	588	12	576	2.04	8.33	1.3	21.8	-41.1
13	365	12/31/95	1	0	1	0.00	0.00	.	.	.
		TOTAL	1552	262	1290	16.88				
		MEAN	141.09	23.82	117.27		27.86	2.31	35.30	-40.43

Table A5. OTD and NLDN Lightning Flash Data for January

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
7	3	1/3/96	54	8	46	14.81	25.00	2.2	15.3	-56.8
13	3	1/3/96	14	1	13	7.14	0.00	3.0	0.0	-44.9
5	7	1/7/96	2	0	2	0.00	.	.	.	.
11	7	1/7/96	3	1	2	33.33	0.00	2.0	0.0	-65.3
13	11	1/11/96	1	0	1	0.00	.	.	.	.
5	12	1/12/96	186	11	175	5.91	18.18	1.3	57.2	-31.6
11	12	1/12/96	1	0	1	0.00	.	.	.	.
11	21	1/21/96	7	0	7	0.00	.	.	.	.
4	23	1/23/96	2	0	2	0.00	.	.	.	.
3	25	1/25/96	10	0	10	0.00	.	.	.	.
4	26	1/26/96	6	1	5	16.67	0.00	1.0	0.0	-15.1
3	31	1/31/96	25	6	19	24.00	33.33	3.2	31.6	-48.3
		TOTAL	311	28	283	9.00				
		MEAN	25.92	2.33	23.58		21.43	2.00	34.68	-42.88

Table A6. OTD and NLDN Lightning Flash Data for February

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
9	33	2/2/96	605	126	479	20.83	19.05	1.6	40.7	-37.0
2	34	2/3/96	17	0	17	0.00	.	.	.	.
8	34	2/3/96	5	1	4	20.00	0.00	1.0	0.0	-115.6
1	43	2/12/96	2	0	2	0.00	.	.	.	.
1	47	2/16/96	14	0	14	0.00	.	.	.	.
1	48	2/17/96	5	0	5	0.00	.	.	.	.
6	50	2/19/96	12	7	5	58.33	42.86	2.8	46.3	-53.6
1	51	2/20/96	69	15	54	21.74	20.00	1.4	34.6	-26.0
6	51	2/20/96	7	1	6	14.29	100.00	0.0	69.9	0.0
0	52	2/21/96	56	4	52	7.14	0.00	2.8	0.0	-62.9
6	53	2/22/96	8	1	7	12.50	0.00	2.0	0.0	-32.5
99	58	2/27/96	6	0	6	0.00	.	.	.	.
5	58	2/27/96	2	1	1	50.00	0.00	3.0	0.0	-70.9
6	59	2/28/96	91	30	61	32.97	20.00	1.8	28.2	-28.4
		TOTAL	899	186	713	20.69				
		MEAN	64.21	13.29	50.93		19.89	1.72	39.40	-36.58

Table A7. OTD and NLDN Lightning Flash Data for March

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
4	65	3/5/96	2	2	0	100.00	100.00	0.0	25.1	0.0
13	65	3/5/96	216	26	190	12.04	26.92	2.1	16.2	-29.8
4	66	3/6/96	37	25	12	67.57	60.00	2.2	43.9	-27.3
4	67	3/7/96	1	0	1	0.00	.	.	.	.
5	67	3/7/96	41	10	31	24.39	10.00	2.9	25.2	-31.7
4	68	3/8/96	18	3	15	16.67	0.00	1.0	0.0	-30.0
4	71	3/11/96	7	2	5	28.57	50.00	1.0	46.9	-161.2
12	71	3/11/96	11	1	10	9.09	100.00	0.0	21.7	0.0
12	74	3/14/96	5	0	5	0.00	.	.	.	.
4	75	3/15/96	7	1	6	14.29	0.00	1.0	0.0	-30.1
13	75	3/15/96	14	6	8	42.86	33.33	3.0	45.6	-34.0
2	76	3/16/96	1	0	1	0.00	.	.	.	.
3	76	3/16/96	7	0	7	0.00	.	.	.	.
1	77	3/17/96	110	21	89	19.09	28.57	1.5	47.2	-30.6
1	78	3/18/96	24	4	20	16.67	50.00	1.5	79.0	-38.1
9	78	3/18/96	18	4	14	22.22	25.00	2.0	33.6	-21.9
3	79	3/19/96	26	5	21	19.23	60.00	2.0	17.8	-49.8
11	84	3/24/96	232	27	205	11.64	29.63	1.8	33.7	-28.1
3	85	3/25/96	22	5	17	22.73	0.00	3.0	0.0	-54.6
1	86	3/26/96	177	42	135	23.73	19.05	1.6	37.7	-53.6
1	87	3/27/96	149	20	129	13.42	15.00	1.4	55.9	-34.2
1	88	3/28/96	15	12	3	80.00	41.67	2.1	27.7	-31.5
2	88	3/28/96	1	1	0	100.00	0.00	2.0	0.0	-88.8
0	89	3/29/96	8	0	8	0.00	.	.	.	.
1	90	3/30/96	379	133	246	35.09	12.03	2.0	27.8	-35.3
10	90	3/30/96	17	2	15	11.76	50.00	1.0	163.1	-25.0
2	91	3/31/96	293	83	210	28.33	31.33	1.8	22.1	-26.1
		TOTAL	1838	435	1403	23.67				
		MEAN	68.07	16.11	51.96		24.83	1.89	33.31	-34.88

Table A8. OTD and NLDN Lightning Flash Data for April

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
0	92	4/1/96	4	0	4	0.00	.	.	.	.
9	92	4/1/96	129	41	88	31.78	2.44	2.7	19.0	-33.5
1	93	4/2/96	4	1	3	25.00	0.00	1.0	0.0	-31.3
1	95	4/4/96	144	83	61	57.64	4.82	2.4	26.2	-28.9
0	96	4/5/96	3	1	2	33.33	0.00	1.0	0.0	-18.9
9	96	4/5/96	12	3	9	25.00	33.33	4.5	30.2	-33.0
0	97	4/6/96	1	1	0	100.00	0.00	3.0	0.0	-54.0
9	97	4/6/96	82	12	70	14.63	8.33	1.3	21.9	-26.0
99	98	4/7/96	1	0	1	0.00	.	.	.	.
8	98	4/7/96	31	1	30	3.23	100.00	0.0	90.4	0.0
99	100	4/9/96	3	0	3	0.00	.	.	.	.
0	104	4/13/96	325	109	216	33.54	16.51	2.1	26.5	-31.0
99	105	4/14/96	46	1	45	2.17	100.00	0.0	15.2	0.0
99	106	4/15/96	657	177	480	26.94	15.25	1.9	25.6	-26.7
14	106	4/15/96	51	7	44	13.73	14.29	1.5	29.2	-14.6
13	108	4/17/96	4	2	2	50.00	0.00	1.5	0.0	-40.0
7	109	4/18/96	5	0	5	0.00	.	.	.	.
13	110	4/19/96	94	19	75	20.21	10.53	1.7	9.9	-21.7
7	111	4/20/96	49	48	1	97.96	43.75	2.4	9.3	-18.3
13	111	4/20/96	566	225	341	39.75	11.11	2.4	23.1	-23.4
7	112	4/21/96	147	45	102	30.61	31.11	2.4	27.0	-31.7
12	112	4/21/96	6	1	5	16.67	0.00	1.0	0.0	-40.6
13	112	4/21/96	31	9	22	29.03	11.11	1.9	15.5	-30.3
99	113	4/22/96	3	1	2	33.33	100.00	0.0	48.5	0.0
14	113	4/22/96	990	303	687	30.61	19.14	2.4	21.4	-29.5
13	114	4/23/96	46	8	38	17.39	25.00	1.3	11.9	-47.0
6	115	4/24/96	1	0	1	0.00	.	.	.	.
12	115	4/24/96	5	0	5	0.00	.	.	.	.
13	117	4/26/96	42	11	31	26.19	0.00	2.5	0.0	-19.3
5	118	4/27/96	1	0	1	0.00	.	.	.	.
		TOTAL	3483	1109	2374	31.84				
		MEAN	116.10	36.97	79.13		16.14	2.26	22.23	-27.54

Table A9. OTD and NLDN Lightning Flash Data for May

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
11	123	5/2/96	30	1	29	3.33	0.00	1.0	0.0	-11.6
11	124	5/3/96	395	44	351	11.14	13.64	2.6	18.7	-21.8
4	127	5/6/96	10	0	10	.	.	.	.	.
5	127	5/6/96	250	106	144	42.40	4.72	2.1	18.3	-24.3
10	127	5/6/96	401	217	184	54.11	23.96	2.9	13.9	-20.5
5	128	5/7/96	27	8	19	29.63	12.50	1.9	14.5	-11.9
10	128	5/7/96	42	7	35	16.67	0.00	1.7	0.0	-41.6
10	130	5/9/96	33	2	31	6.06	0.00	1.5	0.0	-99.1
5	131	5/10/96	5	2	3	40.00	0.00	2.0	0.0	-19.0
6	131	5/10/96	10	1	9	10.00	0.00	1.0	0.0	-18.6
5	132	5/11/96	176	61	115	34.66	31.15	2.2	45.0	-30.6
11	132	5/11/96	289	52	237	17.99	11.54	2.9	11.4	-29.1
10	133	5/12/96	26	6	20	23.08	0.00	1.5	0.0	-33.7
11	133	5/12/96	1	0	1	0.00	.	.	.	.
10	134	5/13/96	47	17	30	36.17	0.00	2.9	0.0	-45.3
9	137	5/16/96	1	0	1	0.00	.	.	.	.
8	143	5/22/96	16	4	12	25.00	0.00	2.0	0.0	-27.4
8	145	5/24/96	35	5	30	14.29	0.00	1.2	0.0	-18.2
2	146	5/25/96	4	2*	0	50.00*	0.00	2.5*	0.0	-18.6*
8	146	5/25/96	19	0	19	.	.	.	.	.
2	147	5/26/96	8	1	7	12.50	0.00	2.0	0.0	-39.9
7	147	5/26/96	16	1	15	6.25	100.00	0.0	15.6	0.0
3	148	5/27/96	64	26	38	40.63	19.23	3.1	43.0	-43.0
1	149	5/28/96	6	1	5	16.67	100.00	0.0	88.6	0.0
2	150	5/29/96	147	56	91	38.10	17.86	2.7	17.1	-30.8
8	150	5/29/96	144	66	78	45.83	19.70	2.8	13.8	-29.6
2	151	5/30/96	20	6	14	30.00	33.33	2.0	10.9	-32.2
8	151	5/30/96	32	3	29	9.38	0.00	2.0	0.0	-17.7
2	152	5/31/96	10	3	7	30.00	33.33	2.0	43.9	-30.2
7	152	5/31/96	28	8	20	28.57	37.50	1.4	41.0	-36.7
		TOTAL	2292	706	1586	30.80				
		MEAN	76.40	23.53	52.87		17.71	2.55	21.76	-26.64

*Corrected values used after collocation procedure matched 7 NLDN flashes.

Table A10. OTD and NLDN Lightning Flash Data for June

Orbit Num	Julian Day	M/D/Y	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
2	153	6/1/96	9	0	9	0.00	.	.	.	.
8	153	6/1/96	200	87	113	43.50	16.09	2.5	40.3	-31.8
7	154	6/2/96	40	9	31	22.50	11.11	2.0	16.2	-45.5
1	156	6/4/96	103	21	82	20.39	28.57	2.1	31.9	-25.7
6	156	6/4/96	12	2	10	16.67	0.00	4.0	0.0	-49.9
1	157	6/5/96	21	8	13	38.10	0.00	2.2	0.0	-31.5
1	158	6/6/96	27	0	27	0.00	.	.	.	.
6	158	6/6/96	32	19	13	59.38	26.32	3.1	13.7	-23.1
1	159	6/7/96	598	275	323	45.99	13.45	2.3	15.9	-24.7
0	160	6/8/96	785	216	569	27.52	15.28	2.6	16.5	-28.2
5	160	6/8/96	1	1	0	100.00	0.00	1.0	0.0	-30.0
6	160	6/8/96	478	113	365	23.64	7.08	2.2	38.7	-39.9
0	161	6/9/96	1	0	1	0.00	.	.	.	.
6	161	6/9/96	373	74	299	19.84	13.51	2.9	21.3	-52.6
0	163	6/11/96	2	0	2	0.00	.	.	.	.
99	165	6/13/96	4	0	4	0.00	.	.	.	.
0	165	6/13/96	73	46	27	63.01	4.35	2.2	12.2	-27.2
5	165	6/13/96	2	0	2	0.00	.	.	.	.
0	166	6/14/96	119	45	74	37.82	28.89	2.7	20.0	-29.6
6	166	6/14/96	2	1	1	50.00	0.00	1.0	0.0	-18.8
99	167	6/15/96	7	1	6	14.29	0.00	8.0	0.0	-21.0
6	167	6/15/96	18	8	10	44.44	0.00	2.8	0.0	-67.0
14	167	6/15/96	5	1	4	20.00	0.00	4.0	0.0	-11.3
1	168	6/16/96	18	0	18	0.00	.	.	.	.
99	169	6/17/96	151	28	123	18.54	14.29	3.2	19.0	-33.2
13	169	6/17/96	93	20	73	21.51	20.00	3.1	14.8	-41.3
5	170	6/18/96	46	6	40	13.04	0.00	4.0	0.0	-37.7
13	170	6/18/96	359	82	277	22.84	12.20	2.2	12.4	-33.2
99	171	6/19/96	204	76	128	37.25	6.58	3.1	33.4	-27.2
99	172	6/20/96	333	83	250	24.92	15.66	2.8	11.3	-29.7
5	172	6/20/96	21	7	14	33.33	14.29	1.5	54.0	-47.2
6	172	6/20/96	297	101	196	34.01	16.83	2.6	16.9	-25.8
14	172	6/20/96	4	0	4	0.00	.	.	.	.
6	173	6/21/96	26	2	24	7.69	0.00	1.0	0.0	-37.3
14	173	6/21/96	34	4	30	11.76	25.00	3.3	24.2	-57.2
13	174	6/22/96	309	90	219	29.13	11.11	2.4	14.2	-30.2
5	175	6/23/96	4	2	2	50.00	0.00	1.0	0.0	-26.1
6	175	6/23/96	209	50	159	23.92	2.00	1.3	80.7	-37.9
14	175	6/23/96	566	213	353	37.63	11.27	3.0	11.0	-29.3
3	176	6/24/96	3	0	3	0.00	.	.	.	.
4	176	6/24/96	54	2	52	3.70	0.00	3.0	0.0	-56.1
12	176	6/24/96	301	143	158	47.51	4.20	2.0	9.4	-23.9
4	177	6/25/96	42	17	25	40.48	0.00	1.6	0.0	-28.5
2	179	6/27/96	354	171	183	48.31	14.04	2.5	14.6	-32.1
3	180	6/28/96	94	40	54	42.55	2.50	2.1	15.1	-35.1
11	180	6/28/96	10	1	9	10.00	0.00	2.0	0.0	-30.0
10	181	6/29/96	10	6	4	60.00	0.00	1.7	0.0	-25.5
		TOTAL	6454	2071	4383	32.09				
		MEAN	137.32	44.06	93.26		12.07	2.48	18.50	-30.70

Table A11. OTD and NLDN Lightning Flash Data for July

Orbit Num	Julian Day	M/D/Y FLASH	OTD FLASH	NLDN FLASH	OTD-NLDN FLASH	% CG FLASH	% POS	NEG MULT	POS MPC (kA)	NEG MPC (kA)
3	183	7/1/96	1	0	1	0.00	.	.	.	.
11	183	7/1/96	16	2	14	12.50	0.00	1.5	0.0	-55.2
12	183	7/1/96	15	3	12	20.00	0.00	1.7	0.0	-18.2
4	184	7/2/96	11	1	10	9.09	0.00	3.0	0.0	-91.2
13	184	7/2/96	4	0	4	0.00	.	.	.	.
3	185	7/3/96	161	33	128	20.50	3.03	1.9	74.4	-40.4
4	185	7/3/96	18	6	12	33.33	0.00	1.5	0.0	-48.6
13	185	7/3/96	3	1	2	33.33	0.00	1.0	0.0	-24.1
4	186	7/4/96	17	9	8	52.94	0.00	1.6	0.0	-27.0
13	186	7/4/96	374	125	249	33.42	13.60	2.5	16.8	-27.0
2	188	7/6/96	1	0	1	0.00	.	.	.	.
3	188	7/6/96	23	9	14	39.13	11.11	2.0	20.4	-30.0
11	188	7/6/96	4	0	4	0.00	.	.	.	.
3	189	7/7/96	81	16	65	19.75	25.00	2.1	27.5	-49.9
12	189	7/7/96	54	10	44	18.52	10.00	2.7	7.7	-25.2
2	190	7/8/96	34	9	25	26.47	11.11	3.5	40.5	-29.3
3	190	7/8/96	2	0	2	0.00	.	.	.	.
2	191	7/9/96	4	1	3	25.00	0.00	2.0	0.0	-17.8
3	191	7/9/96	4	0	4	0.00	.	.	.	.
11	191	7/9/96	89	49	40	55.06	10.20	2.8	9.5	-27.7
11	192	7/10/96	7	1	6	14.29	0.00	1.0	0.0	-35.5
12	192	7/10/96	5	2	3	40.00	0.00	2.5	0.0	-22.9
1	194	7/12/96	4	1	3	25.00	0.00	1.0	0.0	-43.3
2	195	7/13/96	3	2	1	66.67	0.00	2.0	0.0	-42.0
11	195	7/13/96	25	11	14	44.00	0.00	1.8	0.0	-24.5
1	196	7/14/96	68	37	31	54.41	2.70	2.5	20.9	-53.3
10	196	7/14/96	440	201	239	45.68	6.47	2.7	13.6	-30.2
2	197	7/15/96	18	6	12	33.33	33.33	1.5	28.2	-14.2
1	198	7/16/96	26	8	18	30.77	0.00	2.6	0.0	-25.3
10	198	7/16/96	16	6	10	37.50	0.00	2.8	0.0	-28.4
2	199	7/17/96	12	6	6	50.00	50.00	1.3	18.1	-17.2
1	200	7/18/96	20	4	16	20.00	25.00	1.0	18.4	-16.6
1	201	7/19/96	50	10	40	20.00	10.00	2.3	87.8	-33.6
10	203	7/21/96	86	56	30	65.12	5.36	2.3	13.6	-26.9
0	204	7/22/96	5	1	4	20.00	0.00	1.0	0.0	-46.1
1	204	7/22/96	35	20	15	57.14	10.00	3.3	53.2	-23.0
0	205	7/23/96	684	460	224	67.25	17.83	2.7	9.9	-20.7
9	205	7/23/96	19	3	16	15.79	100.00	0.0	35.8	0.0
0	206	7/24/96	113	30	83	26.55	16.67	3.0	25.8	-32.3
1	206	7/24/96	42	9	33	21.43	11.11	3.0	12.8	-17.9
9	206	7/24/96	227	75	152	33.04	18.67	2.0	16.6	-27.0
99	207	7/25/96	9	4	5	44.44	0.00	2.8	0.0	-40.6
0	207	7/25/96	397	150	247	37.78	14.00	2.8	21.9	-32.3
8	207	7/25/96	1	1	0	100.00	0.00	2.0	0.0	-26.3
0	208	7/26/96	107	20	87	18.69	15.00	2.8	40.4	-29.9
9	208	7/26/96	151	41	110	27.15	17.07	2.7	14.5	-47.8
99	209	7/27/96	32	9	23	28.13	22.22	6.1	21.8	-27.0
0	209	7/27/96	36	22	14	61.11	9.09	2.6	9.7	-30.0
8	209	7/27/96	100	7	93	7.00	57.14	2.7	8.5	-22.2
99	211	7/29/96	121	25	96	20.66	8.00	2.6	23.4	-28.7
8	211	7/29/96	52	28	24	53.85	3.57	1.8	41.3	-39.7
99	212	7/30/96	8	3	5	37.50	0.00	2.0	0.0	-21.9
0	212	7/30/96	11	3	8	27.27	66.67	3.0	14.0	-98.6
8	212	7/30/96	127	67	60	52.76	13.43	2.6	25.2	-42.9
99	213	7/31/96	159	54	105	33.96	12.96	2.7	23.3	-31.8
7	213	7/31/96	1	0	1	0.00	.	.	.	.
		TOTAL	4133	1657	2476	40.09				
		MEAN	73.80	29.59	44.21		13.34	2.58	16.87	-29.26